UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN No. 2 NOVEMBER 1905

TESTS OF HIGH-SPEED TOOL STEELS ON CAST IRON

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In most manufacturing processes it becomes necessary to change the form of materials in order to bring them to the desired shape for use. Among the metals used in the construction of engineering structures, including the almost endless variety of steam and gas engines, compressors, pumping machinery, marine and locomotive engines, special machinery and machine tools, it is evident that cast iron and steel represent by far the chief constituents of such machines. For the manufacture of all the various parts of these structures and machines there has been designed a great variety of machine tools. In these machine tools are placed the pieces whose shape it is desired to change, and a properly formed and hardened piece of steel is made to cut away a part of the material. The steel used for making the tool for thus cutting the softer material is called Tool Steel. The time required to cut away the necessary amount of metal is an nportant factor in the cost of the piece under construction. It evident that the relative hardness of the tool steel and the rial it cuts, as well as the speed at which the cutting is at-d, will be important factors in the time required to do the of the durability of the tool steel used. These facts ually exerted a potent influence upon the manufac-steel and they have constantly improved the quality of their product. On the other hand, the demand for stronger and lighter materials of construction has increased the density and hardness of many materials already used, and brought into common use new materials, such as cast steel, ferro steel, chilled iron, etc., and these have imposed severer duties on the tool steels designed to cut them. The same rivalry that has existed between armor plate and the projectile intended to pierce it has existed between the tool steels and the materials they are designed to cut. Until quite recently, the rate at which tool steel could cut the various metals was from 10 to 40 feet per minute, varying with the metals cut and with the area of the cross section removed. If a higher rate of cutting was attempted, the point of the tool used became hot, lost its temper and immediately wore away. During the years 1898 to 1900, Messrs. Taylor and White, at the Bethlehem Steel Works, South Bethlehem, Pennsylvania, were seeking to discover what constituents could be combined with tool steel, and what special temperature treatment it should receive that would increase its cutting speed. As the result of their experiments, there was exhibited at the Paris Exposition of 1900 a lathe using a tool steel which removed chips of soft steel at a cutting speed of from 60 to 180 feet per minute. These chips were so hot that they turned blue upon cooling. The point of the tool steel maintained its cutting edge even when running at a dull red glow. It was natural that to such tools should have been given the name of High-Speed Tool Steels.

Properties of Tool Steels

At the time of Taylor and White's first experiments, Mushet and Jessop tool steels of the self-hardening type were in general use. According to Mr. F. Reiser in an article on high-speed steel in "Stahl and Eisen", January 15, 1903, they had the following chemical composition:

Carbon 2.0%	Manganese 2.5%	Silicon 1.3[illegible]
Tungsten 5.0%	Chromium 0.5%	

The self-hardening property is called into play by manganese, an element which favors the combining of the with the iron. These steels were tempered simply by [illegible] a temperature of 1600° F. and then cooling in air. Jessop tools, however, did not prove durable at although they were far in advance of the ordina[illegible] and chromium was substituted for manganese with good results. The chromium steels required an entirely different treatment, as was found by Messrs. Taylor and White in their experiments at the Bethlehem Steel Works.

The exact chemical compositions of the new tool steels are secrets of the separate makers, and probably vary; however, it is known that the steels contain the following elements in varying quantities: carbon, tungsten, chromium, manganese, molybdenum and titanium. They usually run high in these combining elements, the Taylor-White steel having as high as 12% of tungsten and 4% of chromium, while Böhler Brothers' Styrian steel, according to Mr. Reiser, has a maximum of 28% of other elements. With this increase the carbon element has greatly decreased; most of it combines with tungsten, chromium and the other elements at high temperatures, remains in that state when cooled in an air blast and forms carbides of extreme hardness and durability at high temperatures. For best results of toughness and hardness these high-speed steels require for tempering a temperature of from 2000° to 2250° F., or a white heat bordering on the fusion point, and are then cooled in an air blast, lead bath or oil bath according to the different makers. Mr. Reiser in his discussion has for this reason correctly named them "superheated steels."

Advantages of High-Speed Steels

High-speed steels, due to their hardness and durability at high temperatures, retain their edge when cutting at extremely high speeds, cases having been noted in which the tool worked at dark-red heat without losing its edge. As can be seen from the tables, the speeds obtained are from three to four times those obtained with ordinary carbon steels. This of course means an increased output for a given shop and a consequent increase in the returns. This is not the only advantage of high-speed steel. It has been proved that such steel is more economical from the power standpoint, a given power removing a greater quantity of metal per unit of time at high speed than at slow speed. Of course the total power required is increased, but the increase is by no means proportional to the increase in the amount of work done.

There is, however, one condition that must be carefully considered before the introduction of high-speed steels in a shop. Machine tools constructed to use the old carbon steels are limited in capacity and will not stand the heavy stresses to which they would be subjected if using high-speed steels at maximum speeds and feeds. This condition, however, is being met by the machine-tool builders, who are now designing and building especially heavy tools with powerful feed mechanisms with a view towards obtaining the highest possible efficiency of the steel used.

In the following pages are described the experiments made by Mr. H. B. Dirks, Assistant in Mechanical Technology, Engineering Experiment Station, in the shops of the College of Engineering at the University of Illinois. These experiments have been in progress for nearly a year, and every effort has been made to obtain useful and correct results.

For convenience, the subject has been divided into the following parts: I. The Tool Steels Used. II. The Cast-Iron Test Pieces. III. Details of the Tests. IV. Results of the Experiments. V. Summary of Results. VI. Reference List of Articles on High-Speed Steels. Appendix,—giving instructions furnished by makers for hardening the steels used.

I. The Tool Steel Used

(*a*) *The Brands Used*

The following tool steels were used in these trials:

1. Styrian marked "Böhler Rapid"
2. Jessop's "Ark"
3. McInnes's "Extra"
4. Mushet's "Special"
5. "Air Novo"
6. "Rex"
7. "Poldi"
8. "A and W" (Armstrong and Whitworth)

The first six came from the American market. Poldi and "A and W" were furnished by the American Radiator Company, having been used in its foreign factories. With the exception of the Mushet, the steels used were donated for the proposed tests by the makers or agents. The Mushet was taken from stock purchased in the open market. There are doubtless other kinds of steel which could have been tested, but these eight brands were most familiar and accessible to the writers, and it is believed that they represent fairly well the brands commonly used at the present time by American manufacturers.

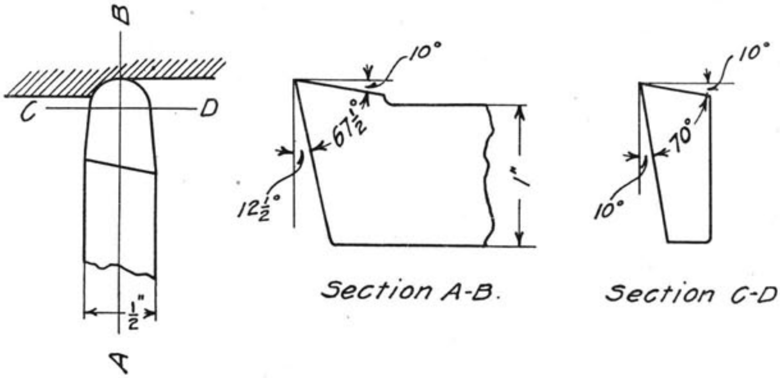

FIG. 4. SHAPE OF CUTTING TOOLS

(*b*) *Size and Shape of Tools*

The size of the bars of steel from which the tools were made was $\frac{1}{2}$ in. by 1 in. for the steels from the American market. The Poldi bar was $\frac{3}{4}$ in. by $1\frac{3}{4}$ in., and the "A and W" bar was $\frac{3}{4}$ in. by $1\frac{1}{4}$ in. The shape of the tool used in the tests is shown in Fig. 4. The front clearance was $12\frac{1}{2}°$, the top rake was 10° and the side rake was also 10°. These angles were carefully maintained throughout the tests, the angles being measured with a bevel protractor after each grinding.

Experiments relating to the proper shape of tools have been made by Professor J. T. Nicolson,* and the writers were guided in selecting proper tool angles by the recommendations of his paper. Professor Nicolson says: "Tools should therefore be ground for maximum endurance in the cutting of cast iron in ordinary shop practice so that their true cutting angles are about 81°, or if they are allowed 6° clearance for working on the level of the lathe centers, they should have an included angle of about 75°.

(*c*) *Tempering and Tempering Apparatus*

Directions for forging and hardening the various steels used were furnished by the manufacturers. For convenience, these directions are published in the Appendix. It will be seen that most of the steels were to be hardened in an air blast. The "A

*Experiments with a Lathe Tool Dynamometer. See Trans. A. S. M. E., Vol. 25, 1904, page 658 et seq.

and W'' steel was the only one in which oil was recommended for cooling, and then only after the cutting edge of the tool had been cooled to a cherry-red in the air blast. An air blast apparatus was designed and constructed for carrying out the instructions relating to the proper preparation of the tools. This is shown in Fig. 5.

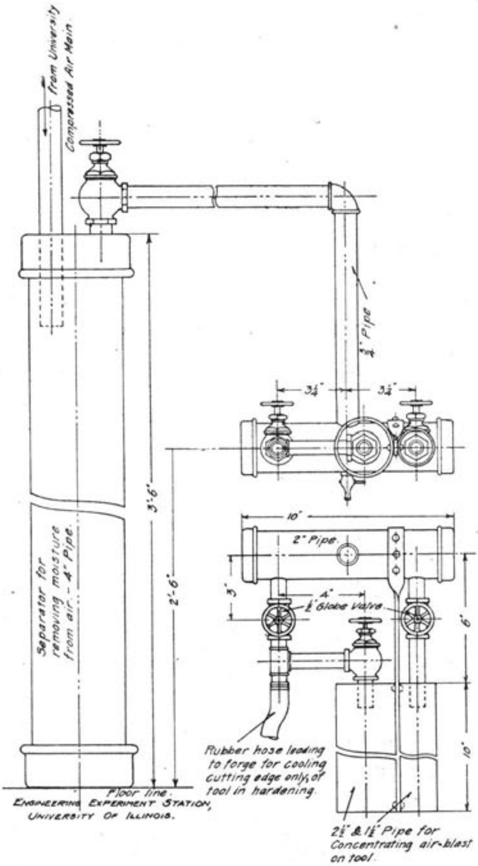

FIG. 5. AIR BLAST APPARATUS

The apparatus consists of the 4-in. separating pipe, 3 ft. 6 in. long to which is connected the header of 2-in. pipe about 10 in. long. The dimensions and construction are shown in the figure. The tools to be hardened are inserted in the short lengths of $1\frac{1}{2}$ or $2\frac{1}{2}$-in. pipes which serve to concentrate the air blast on the tools. A rubber hose with a $\frac{1}{8}$-in. nozzle in the end is also attached to one opening, so that a strong air blast may be directed on the edge of the tool when first removed from the fire. The tools were heated in an ordinary forge with a clear coke fire. The fire was burned long enough before putting in the tool to drive off any sulphur. Care was also taken to have plenty of coke above and below the tool so that no cold blast should strike the tool while it was being heated.

II. The Cast-Iron Test Pieces

In order that the results of the tests might be of general application, it was advisable that the cast-iron test pieces be the product of several commercial foundries. Several manufacturers throughout the State agreed to furnish sample test pieces representing the grade of cast iron used in their respective foundries. A standard size of test piece was therefore decided upon, and blue prints and patterns of it sent to the different manufacturers. This standard test piece is shown in Fig. 6. The outer diameter is the maximum the lathe will swing over the carriage. This test piece was made hollow for several reasons. A solid test piece becomes soft toward the center and is more likely to contain blow holes. Test pieces of small diameter become springy and consequently produce inaccuracies in the results. The high angular velocity necessary with small diameters is also undesirable. The first test piece used in the preliminary trials was 18 in. long. This was found to be too short, the tool having to be reset too often. In Fig. 3 is given a view of all the test pieces used in the trials. These test pieces do not all conform to the standard test piece, the American Radiator Company having sent test pieces with a 6-in. core instead of a 3-in. core, from several of its plants, that being a more representative casting from its foundries. The test pieces received from the various companies, their identification marks and reference numbers are shown in Table 1.

TABLE 1

RESULTS OF HARDNESS TESTS AND IDENTIFICATION MARKS

OF

CAST-IRON TEST PIECES USED IN THE TESTS

Name of company sending test pieces		Identification mark	Test reference No.	Hardness by drill test
American Radiator Co. Chicago, Ill.	Pierce plant.	3 ″ core	3	94.2
			4	109.2
			5	102.0
	Michigan Plant.	5-8-05	6	128.8
			7	86.5
		6 ″ core	8	94.3
			9	138.6
			10	106.8
			11	109.3
	Detroit plant	D. P. 1	12	100.0
		D. P. 2	13	106.6
		D. P. 3	14	117.2
		D. P. 4	15	132.0
		D. P. 5	16	109.8
		D. P. 6	17	90.3
	——— plant.	5-17-05	18	107.0
			19	117.2
			20	113.9
	——— plant.	B	21	124.8
		5-26-05	22	167.5
			23	122.2
	——— plant.	B	24	111.2
		6-2-05	25	102.4
			26	95.9
Crane Company Chicago, Ill.	Ferro Steel.	F. S.	1	342.0
	Grey Iron.		27	132.0
Root & Vandervoort Eng'g Co...... East Moline, Ill.			2	175.0
University of Illinois.............. Urbana, Ill.		U. I.—1	28	114.5
		U. I.—2	29	195.0
		U. I.—3	30	124.2
		U. I.—4	31	124.5
		U. I.—5	32	123.2

A comparative hardness test was made on all samples, comparison being made with a standard piece of soft cast iron of equal density throughout, the chemical analysis of which is as follows:

Combined Carbon = .147%	Silicon = 2.35%	Sulphur = .07%
Graphite = 5.03 %	Manganese = .33%	Phosphorus = 1.06%

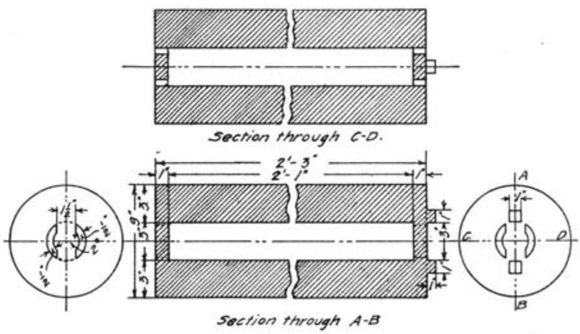

FIG. 6. STANDARD TEST PIECE

The hardness of cast iron or any other metal as indicated by a drill test is probably as fair an indication of the particular quality of the metal that affects the cutting speed as is obtainable by any process in use at the present time. This hardness test is in itself a cutting-speed test in which the cutting speed is not varied, but is held constant and the rate of feed allowed to vary, the cutting speed and rate of feed in all probability bearing some constant relation to each other. Fig. 7 is a graphical chart giving the results of the hardness tests on the test pieces used in the experiments. The tests were made with a drill press as shown in Fig. 8. A constant load of 312 pounds was applied on the spindle of the drill press by means of the weighted lever. With the spindle rotating at a constant speed of 87 r. p. m., the rate of feed of the drill in inches per minute was measured, readings being taken for every $\frac{1}{8}$ in. of depth drilled. The drill used in these tests was a Morse standard $\frac{1}{2}$-in. twist drill ground to an angle of $62\frac{1}{2}°$. As, however, there was some liability of variation in the sharpness of the drill, thus affecting its rate of feed, a uniform piece of cast iron was first drilled into, readings taken, and then the test made on the test piece. A comparison was thus always made with this same piece of cast iron, eliminating any

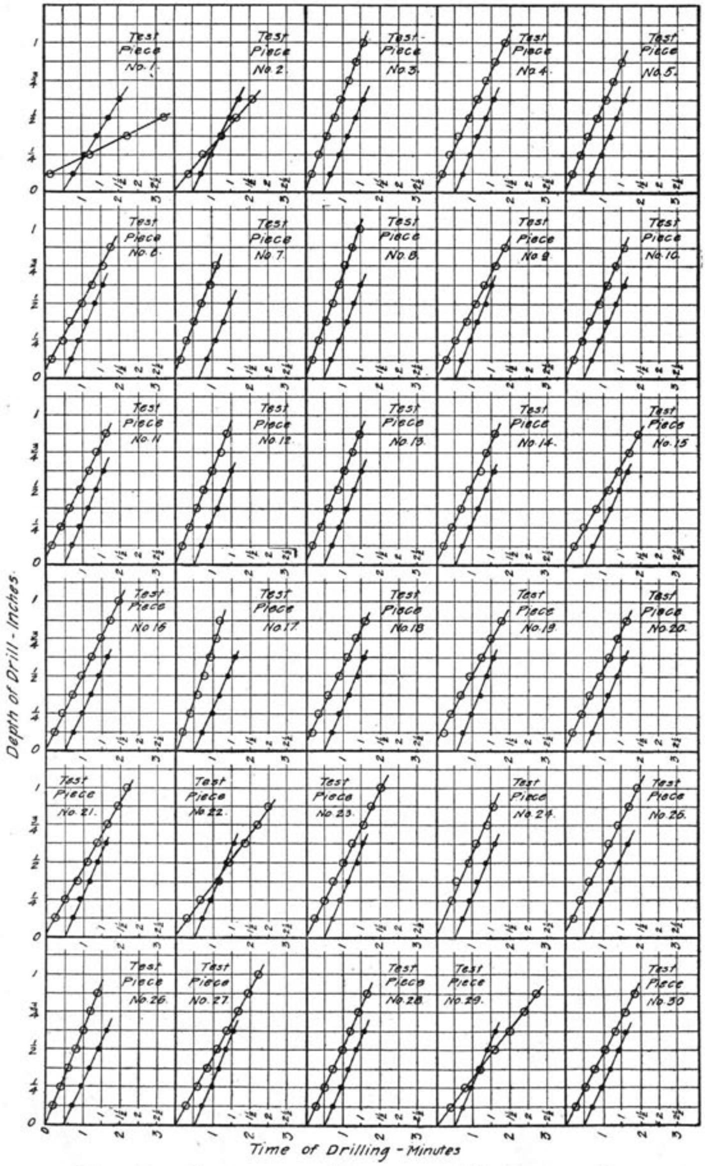

FIG. 7. GRAPHICAL CHART OF HARDNESS DRILL TESTS MADE ON CAST-IRON TEST PIECES

small variation in the sharpness of the drill. In Fig. 7 the curves drawn through the dots represent the standard cast iron, and those drawn through the circles represent the test piece. Thus for test piece No. 1 the rate of feed is about .174 in. per minute, while in drilling the standard cast iron, the rate of feed is about .595 in. per minute. The hardness as used later and as expressed in Table 1 is $\frac{.595}{.174} \times 100 = 342$. Assuming 100 as the hardness of the standard cast iron, Table 1 gives the results obtained from these tests. This method of expressing the hard-

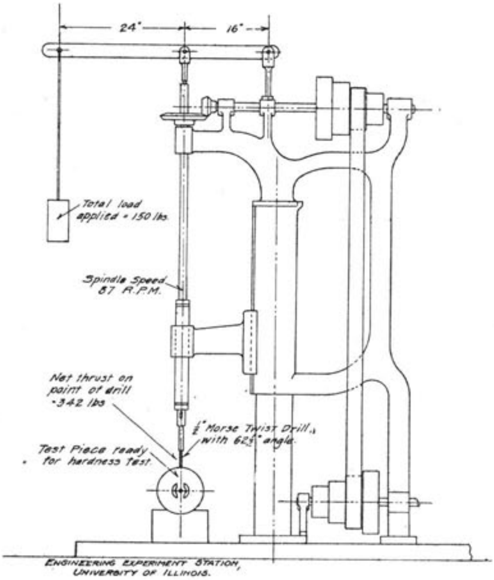

FIG. 8. DRILL PRESS, SHOWING METHOD OF MAKING HARDNESS TESTS ON CAST-IRON TEST PIECES

ness of cast iron was also used by Professor J. T. Nicolson in his experiments with high-speed tool steels made at the Manchester Municipal School of Technology, Manchester, England.* In these experiments the tangent of the angle made by the curve was used as the hardness.

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*Report of experiments made at Manchester Municipal School of Technology, London Engineering, October 30 and November 13, 1903.

III. Details of the Tests

(a) *Apparatus*

The apparatus used in conducting the tests consisted mainly of a high-speed lathe deriving its power from a two-phase induction motor by means of belting and a countershaft, the power required being measured by a polyphase wattmeter. The general arrangement is shown in Fig. 1 and Fig. 9. The lathe used (see Fig. 2 and Fig. 10) was a Pratt and Whitney high-speed lathe with a gear box head-stock, taking a maximum length of 3 ft. 9

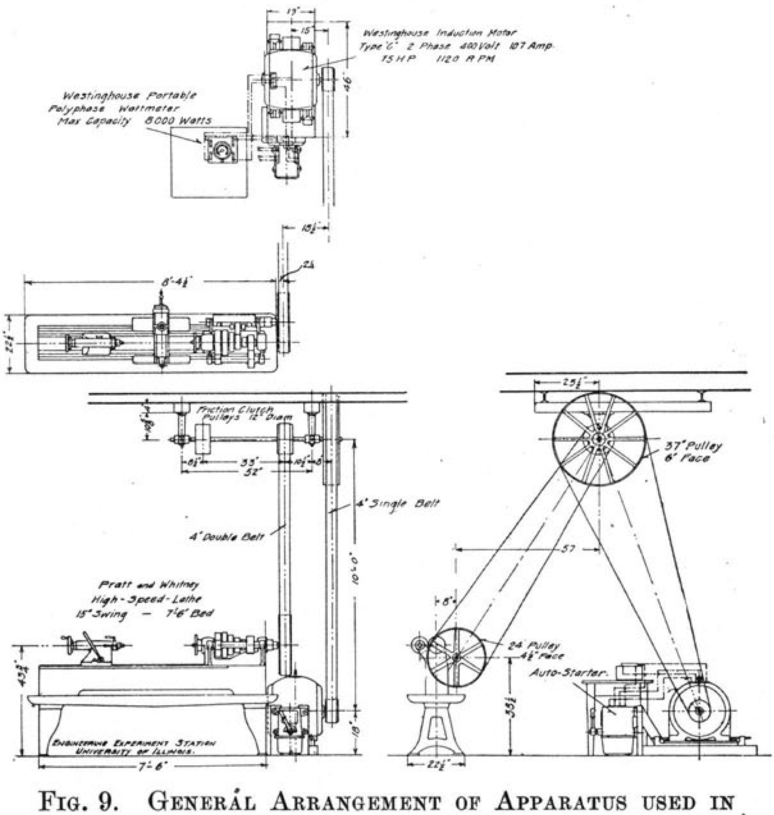

FIG. 9. GENERAL ARRANGEMENT OF APPARATUS USED IN THE TESTS WITH HIGH-SPEED TOOL STEELS

in. between centers and a diameter of 9 in. over the carriage. The power was transmitted from the first motion shaft of the head-stock to the cone gears by means of a long pinion and an intermediate gear, the latter being fastened to the intermediate gear frame which swivels about the first motion shaft. The intermediate gear frame has a substantial slide with rack, pinion and crank by which the intermediate gear is moved to any one of four positions, in which it is locked by the dropping of a pin into suitable holes in the frame, after which movement the frame is swiveled to drop the gear into mesh with the cone gear. The latch handle at each end of the frame holds the frame and gears in position after the gears are in mesh. From the cone gears the power is transmitted either direct to the spindle or through the usual back gears, thus making 8 changes of speed. The speeds and feeds obtainable are shown in Table 2 and Table 3. The feed mechanism is positive, being driven by two gears from the main spindle through a chain of gears to the feed box change and speed gears, thence through the feed rod to the carriage. There are 8 changes possible both for the cross and longitudinal feed. A reverse feed is obtained by shifting the reverse rod.

TABLE 2

FEEDS AND FEED GEARS FOR

PRATT & WHITNEY HIGH-SPEED LATHE

Feeds	Feed Gears	Change Gears	Feed Box Change Gears	Feed Box Speed Gear	Worm	Apron Feed Gear	Rack Pinion	Cross Feed Screw	Feed per one Rev. of Spindle	Rev. of Spindle to 1" Travel
Longitudinal Feed	44 to 88 Forward 42 to 84 Reverse, 28 Intermediate	39 to 78 Outside Change Gears 2–78 Intermediate	48 to 64	38 to 74		22 to 66	18 t–8 P.		.0076	131.6
			60 to 52						.0116	86.2
			68 to 44						.0156	64.1
			78 to 34						.0232	43.1
			48 to 64	76 to 36					.0312	32.0
			60 to 52						.0478	20.9
			68 to 44						.0642	15.6
			78 to 34						.0952	10.5
Cross Feed			48 to 64	38 to 74		76 to 18 with 49 Intermediate		1/8 lead single	.00508	196.8
			60 to 52						.00782	127.7
			68 to 44						.01045	95.7
			78 to 34						.01554	64.3
			48 to 64	76 to 36					.0209	47.8
			60 to 52						.0322	31.1
			68 to 44						.0431	23.2
			78 to 34						.0640	15.6

TABLE 3

Range of Speed Ratios and Surface Speeds for Apparatus Used in High-Speed Steel Tests

Motor Pulley Diameter (1120 r. p. m.)	Revolutions per minute				Surface speed of test piece. Feet per min.	
	Counter-shaft	Lathe Pulley	Lathe Spindle			
			Direct drive	Drive through back gears	Direct drive	Drive through back gears
6 inches	181.62	90.81	68.10 45.40 34.05 27.24	23.48 15.65 11.74 9.38	160.37 106.92 80.19 64.15	55.30 36.80 27.65 22.09
7 inches	211.89	105.94	79.46 52.97 39.73 31.78	27.40 18.26 13.70 10.95	187.10 124.70 93.56 74.84	64.53 43.00 32.26 25.79
8 inches	242.16	121.08	90.81 60.54 45.41 36.32	31.31 20.87 15.65 12.52	213.80 142.60 106.90 85.53	73.74 49.15 36.86 29.48
9 inches	272.43	136.21	102.16 68.11 51.08 40.86	35.23 23.48 17.61 14.10	240.60 160.40 120.30 96.23	82.97 55.30 41.47 33.21
10 inches	302.70	151.30	113.50 75.65 56.74 45.39	39.13 26.10 19.56 15.65	267.30 178.20 133.60 106.90	92.15 61.47 46.06 36.86
11 inches	332.97	166.48	124.90 83.24 62.43 49.94	43.07 28.73 21.52 17.12	294.10 196.00 147.00 117.60	101.40 67.66 50.68 40.32
12 inches	363.24	181.62	136.20 90.81 68.11 54.49	46.96 31.31 23.48 18.78	320.80 213.80 160.40 128.30	110.60 73.74 55.30 44.23

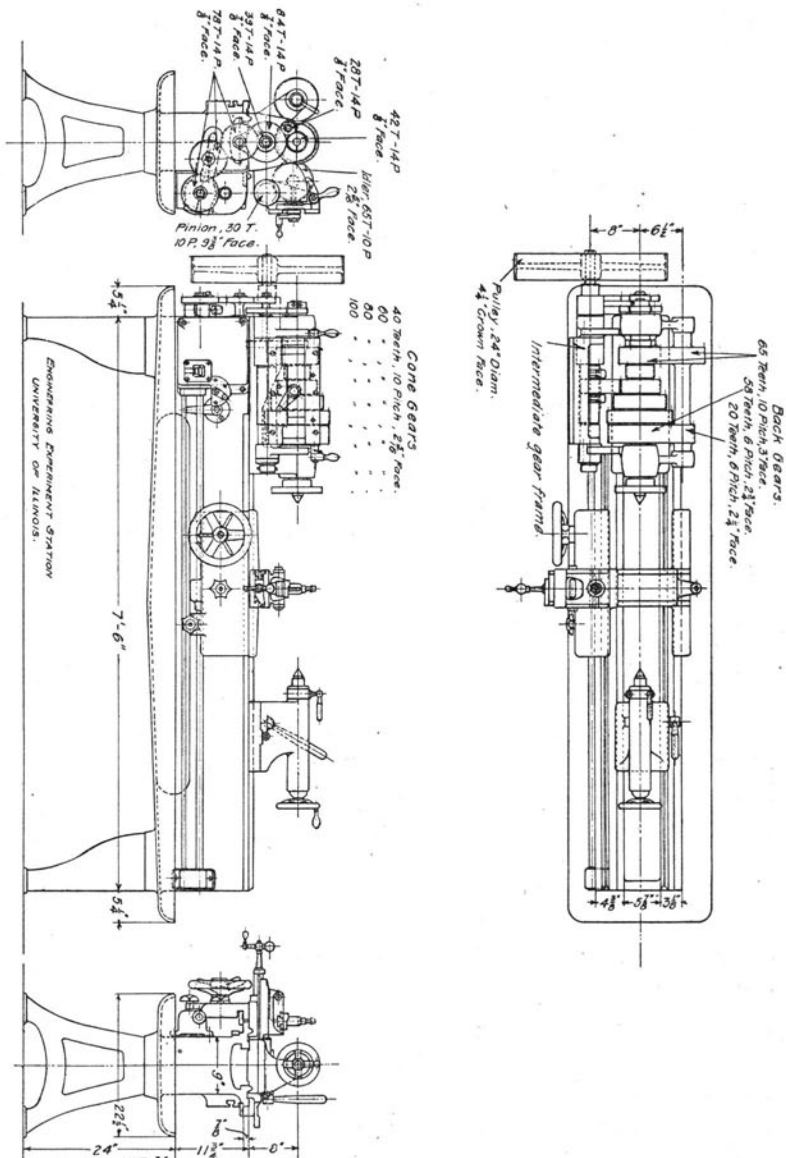

FIG. 10. LATHE USED IN THE TESTS WITH HIGH-SPEED TOOL STEELS

The power was transmitted to the lathe by means of a 4-in. double belt from the 12-in. friction clutch pulley of the countershaft. The countershaft in turn was driven through a 37-in. pulley by a 4-in. single belt from the motor. The motor is on an adjustable base, allowing changes of the motor pulley to be made without changing the length of the belt. In the tests, pulleys ranging from 6 to 12 in. in diameter were used, making possible with the 8 changes of speed on the lathe proper, 56 changes for every diameter of work. As the diameter of the test piece decreased, it was thus possible to keep the speed of the cut constant within very small limits. The motor received its current from the 440 volt main of the University power plant. As shown in Fig. 9, the current passed through an auto-starter and wattmeter into the motor, the auto-starter being used to reduce the electromotive force on the motor at starting, thus diminishing the liability of injury to the motor.

The wattmeter used is known as the Westinghouse portable long scale indicating wattmeter for alternating current circuits, and may be used for either two, three or four-phase circuits. "In principle, the wattmeter consists of a miniature induction motor, having for an armature a metal drum mounted on a shaft, together with a spring and pointer, giving indications on the scale proportional to the power to be measured. There is also a stationary circular core of iron inside the drum to complete the magnetic circuit through the armature As it operates on the induction principle, it has no moving wires and is not affected by external fields." "The polyphase wattmeter used in the tests is a modification of the above, having two drums mounted on the same shaft and revolving in two separate fields. This construction makes a meter which is correct for two or three-phase circuits under all conditions of unbalancing, low power factor, etc., and measures the true energy of the circuit".*

(*b*) *Procedure in Making the Tests*

In the preliminary trials the skin was first removed to bring the test piece to a uniform diameter throughout. This was discontinued in the later trials and a separate series of skin cut trials was run. The test piece having been made ready for the test, the tool to be used was placed in the tool rest in the position

*Taken from instructions for the use of the W. P. L. S. I. Wattmeters.

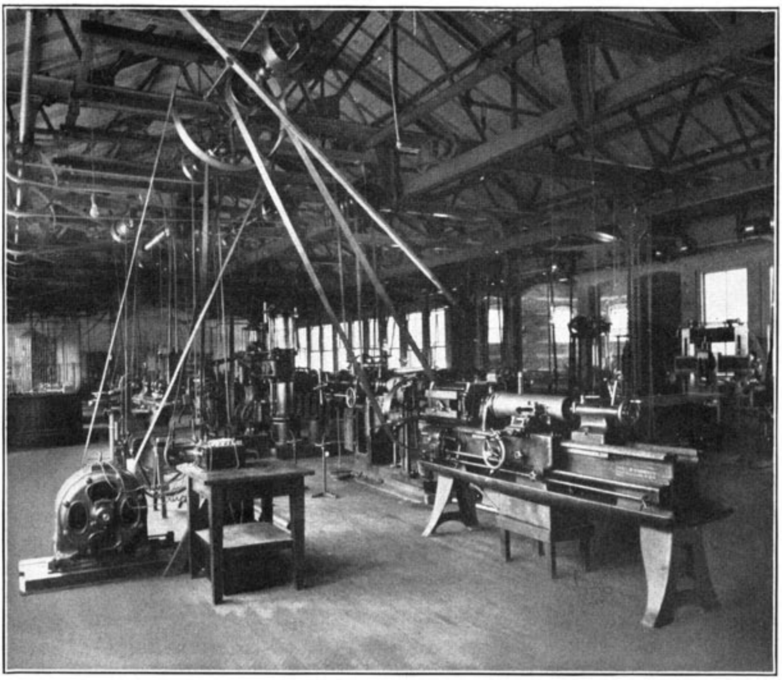

FIG. 1 VIEW IN THE UNIVERSITY OF ILLINOIS MACHINE SHOP SHOWING LOCATION OF LATHE AND MOTOR DRIVE USED IN TESTS WITH HIGH-SPEED TOOL STEELS

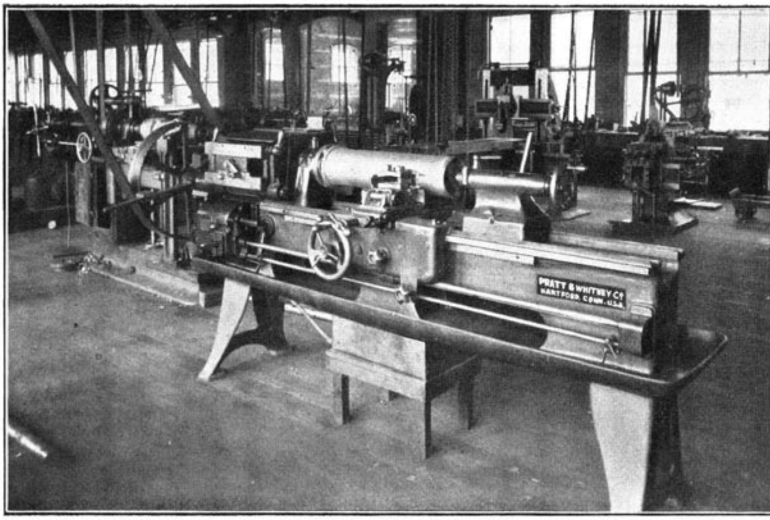

FIG. 2. LATHE USED IN TESTS WITH HIGH-SPEED TOOL STEELS

FIG. 3. CAST-IRON TEST PIECES USED IN TESTS WITH HIGH-SPEED TOOL STEELS

decided upon for all tools and trials, viz., at right angles to the work with the bottom edge of the tool horizontal and the cutting edge of the tool from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. above the center of the work, its exact position being recorded in the log. The diameter of the test piece was then accurately measured in several places and the average recorded in the log. The tool was then fed in by hand until the cutting edge just scraped the bottom of the groove left by the last turning. The graduated disc on the cross feed having been set at zero, with the tool in the above position, the cross feed was turned back a little, and the carriage moved to the right sufficiently for the tool to clear the test piece. The cross feed was then advanced until the graduated disc showed the required cut opposite the index mark. The longitudinal feed or traverse was then set in position and recorded in the log. The diameter of the work and the surface speed required during the trial being known, the size of the pulley to be used on the motor and the position of the driving gear necessary to give the required speed were obtained from a set of curves giving the speed for various diameters of work for each of the 56 changes obtainable. This having been done, the lathe was started and the surface speed tested with a Warner cutmeter. If found to be too far from the required speed, a different combination of motor pulley and cone gear was tried. A satisfactory speed having been obtained, the feed mechanism was started and the lathe allowed to run until the tool had entered the work and was taking the full cut. The lathe was then stopped and the square-case revolution counter, which was actuated by the first motion shaft, set at zero. The lathe was then cleared of all chips and the test started, the exact time of starting and the position of the revolution counter being recorded. During the trials, readings of the revolution counter and also of the wattmeter were taken every two minutes in order to obtain any variations in the cutting speed and the power required. After the expiration of the trial, which occurred either at the time of failure of the tool or at a specified time limit, the tool was withdrawn and the lathe run light under the same conditions of speed as in the trials, in order to observe the electrical horse-power exerted by the motor under these conditions. All cuttings were then collected, weighed and recorded in the log. To facilitate the collection of chips, sheet iron guards were placed on the bed of the lathe.

(*c*) *Description of Methods Adopted for Measuring the Force Required in Cutting*

During the trials readings were taken at regular intervals of the total electrical watts input in the motor, while cutting, and after the tool had been withdrawn, with the lathe running light. The difference between the electrical horse-power with the tool cutting and with the lathe running without the cut should give the net horse-power required for cutting, and if this be multiplied by 33,000 and divided by the cutting speed, we obtain the force required for cutting in pounds. In thus figuring, we assume that the lost horse-power of the drive remains constant from no load to full load. To determine whether or not this was the case, a Prony brake was placed on the cast-iron test piece, as shown in Fig. 11. This could be made to offer the resistance otherwise produced by the cutting tool, and this resistance could be meas-

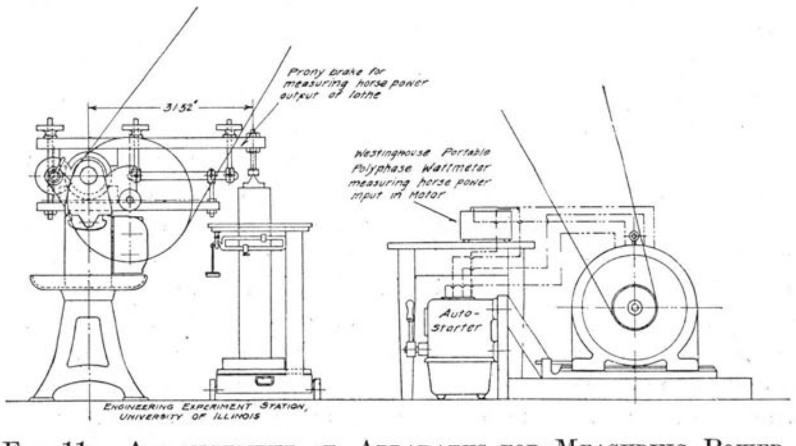

FIG. 11. ARRANGEMENT OF APPARATUS FOR MEASURING POWER ABSORBED BY FRICTION IN THE LATHE, COUNTER-SHAFT AND BELTING

ured at the end of the brake arm by observing the reading on the scale beam of the platform scales. The brake arm was made 31.52 in. in length to facilitate the work of obtaining the horse-power, which would then be $\frac{PN}{2000}$, in which P is the net thrust on the scale in pounds and N the number of revolutions of the brake wheel.

Experiments were made on the lathe for both methods of driving it, either direct or through the back gearing. The results of these experiments are given in Fig. 12. In the same figure is also shown the calibration curve for the motor alone, giving the horse-power output for a known input. The loss in the transmission for any known input could be immediately found, it

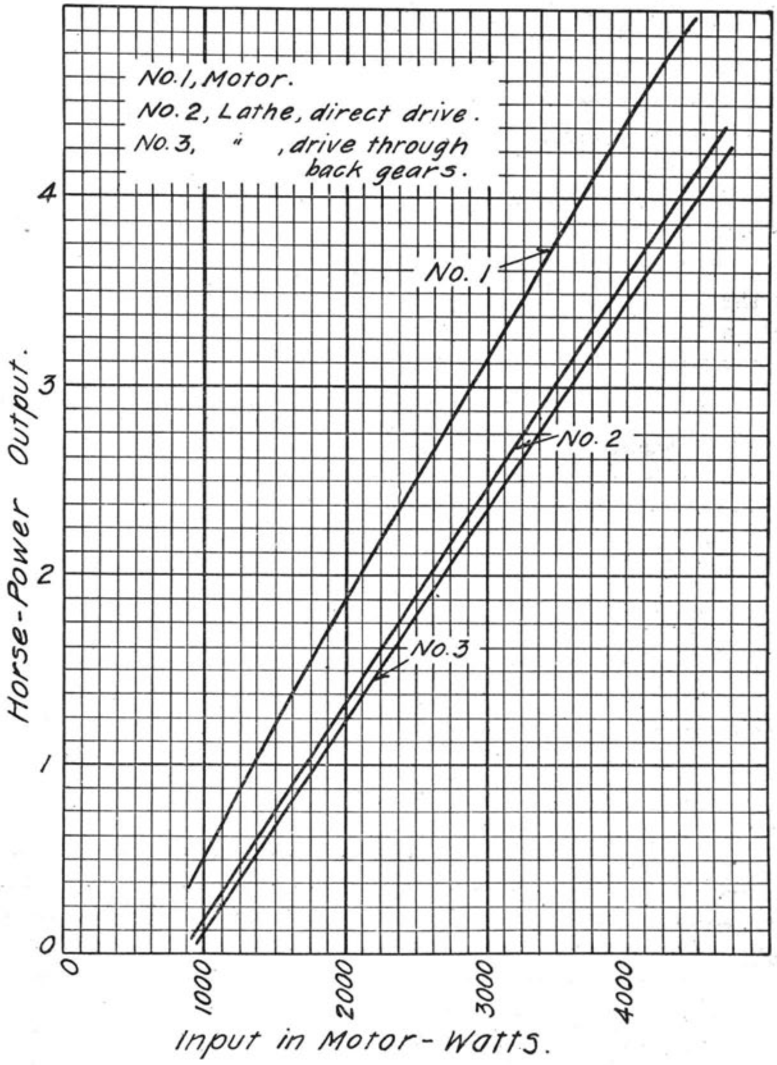

FIG. 12. CURVES GIVING RESULTS OF EXPERIMENTS TO DETERMINE LOSS OF POWER IN LATHE AND COUNTERSHAFT FOR VARYING LOADS

being the vertical distance between the curves at the required load. From the curves it can be seen that it is not constant, but increases at a constant ratio as the load increases. The equations derived from the curves, giving the relation between the net and gross load for both drives, are as follows:

$$(1)\quad N = 0.886G - 0.32 \qquad (2)\quad N = 0.907G - 0.41$$

Where N = net horse-power required for cutting, at the tool point, represented in Fig. 12 by the ordinates of the curves No. 2 and No. 3 according as the lathe is running with or without the back gears; and

G = total horse-power output of motor, represented in Fig. 12 by the ordinates of curve No. 1.

In these equations, (1) applies to the direct drive, and (2) to the drive through the back gears. The net horse-power recorded in Tables VI to X under column 6 contains the above-found correction. The nature of the results will be discussed in Part IV.

IV. Results of the Experiments

The results of the tests made with the eight brands of steel are given in full in Tables I to X below. Some of the most important relations are shown graphically on several plates. There were in fact five sets of experiments made which may properly be referred to as:

(a) The preliminary trials

(b) The skin-cut trials

(c) The endurance trials

(d) Trials to obtain the durability of the steels at different cutting speeds for various sizes of cut, but on cast iron of constant hardness

(e) Trials to obtain the durability of the steels on cast iron of varying hardness.

Tables I to V give for each of the experiments above referred to the observed and calculated data indicated in the 18 columns of results. Some of the most important results given in these tables are:

(a) The cutting speed in feet per minute

(b) The area of section cut

(c) The area machined

(d) The weight of material removed per minute

(e) The relative durability of the tool

(f) The hardness of the test piece

In the same way Tables VI to X give important data for each one of the sets of experiments carried out. The most interesting results which are given by these tables are:

(a) The cutting force on the point of the tool

(b) The net horse-power required to remove the metal

(c) The horse-power required to run the lathe and the countershaft

The headings for the different tables are for the most part clearly indicated. It may be advisable, however, to explain some of them more fully. Referring to Tables I to V, we have in each table the same 18 headings. Columns 4, 5 and 6 give the speeds, cuts and feeds at which the trials were intended to be carried out, as calculated from the size of the pulleys and motor speeds. In columns 7, 8 and 9 are given the actual speeds, cuts and feeds. The cutting speed recorded is the speed in feet per minute of the cylindrical surface of maximum diameter at the point of cutting. The depth of cut is one-half the difference of the diameters of the work before and after cutting. The feed is the advance of the tool per revolution of lathe spindle. Column 10 gives as the area of the section cut the product of the depth of cut and the feed. Columns 12 and 13 give the area of the surface machined. This was obtained by multiplying the cutting speed in feet per minute by the feed in feet per revolution of the spindle. Columns 14 and 15 give the total weight of cuttings removed during the trial and also per minute. These results were obtained by collecting and weighing the cuttings. Column 17 gives the comparative durability of the tool. An entirely arbitrary standard of durability was established as follows: A tool whose cutting edge was worn away .002 in. after one hour's use was considered perfect, its durability being expressed as 100. The ratios of the durability of any other tools to the standard will then be the inverse of the ratios of their rates of wear to the rate of wear of the standard. The wear as assumed for the standard is shown in Figure 13 at x. In the experiments, however, the distance a was measured and x then calculated.

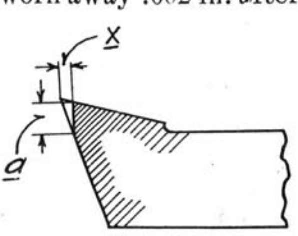

FIG. 13.

TABLE I

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

PRELIMINARY TRIALS

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended		Actual	Actual		Area of Sec. of cut	Duration of Trial
			Speed	Cut & Feed	speed	Cut	Feed		
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Styrian	28	3	55	$\frac{3}{8}$x$\frac{3}{128}$	54.8	$\frac{3}{8}$	.0232	.00870	33
2 "	28	4	35	$\frac{1}{2}$x$\frac{1}{32}$	36.2	$\frac{1}{2}$	.0312	.01560	31
3 "	28	5	30	$\frac{1}{4}$x$\frac{1}{16}$	32.5	$\frac{1}{4}$	.0642	.01600	$15\frac{5}{6}$
4 "	28	6	60	$\frac{1}{8}$x$\frac{3}{32}$	60.5	$\frac{1}{8}$	.0952	.01190	5
5 "	28	7	60	$\frac{1}{8}$x$\frac{1}{16}$	59.6	$\frac{1}{8}$	.0642	.00802	$7\frac{1}{3}$
6 "	28	8	60	$\frac{1}{8}$x$\frac{1}{32}$	58.0	$\frac{1}{8}$	.0312	.00390	10
7 "	28	9	50	$\frac{3}{8}$x$\frac{1}{32}$	52.1	$\frac{3}{8}$	.0312	.01160	15
8 "	28	10	50	$\frac{3}{8}$x$\frac{1}{32}$	47.6	$\frac{3}{8}$	.0312	.01160	8
9 "	28	11	40	$\frac{1}{4}$x$\frac{1}{32}$	41.2	$\frac{1}{4}$	.0312	.00780	8
10 McInnes	1	23	30	$\frac{1}{8}$x$\frac{1}{16}$	28.4	$\frac{1}{8}$	.0642	.00802	10
11 "	1	24	30	"	31.8	$\frac{1}{8}$	.0642	.00802	10
12 "	1	25	30	"	31.9	$\frac{1}{8}$	.0642	.00802	10
13 Novo	1	27	40	$\frac{1}{16}$x$\frac{1}{16}$	40.7	$\frac{1}{16}$	.0642	.00401	22
14 "	1	28	40	"	43.7	$\frac{1}{16}$	.0642	.00401	16
15 "	1	29	40	"	42.5	$\frac{1}{16}$	.0642	.00401	19
16 Styrian	1	30	40	"	41.3	$\frac{1}{16}$	.0642	.00401	$13\frac{1}{2}$
17 Novo	1	31	40	"	41.7	$\frac{1}{16}$	.0642	.00401	13
18 Styrian	27	130	150	$\frac{1}{8}$x$\frac{1}{32}$	152.1	$\frac{1}{8}$	.0312	.00390	$11\frac{1}{2}$
19 Novo	27	131	150	"	153.1	$\frac{1}{8}$	.0312	.00390	9
20 McInnes	27	132	150	"	150.0	$\frac{1}{8}$	.0312	.00390	$1\frac{1}{2}$
21 Styrian	I6	133	110	$\frac{3}{16}$x$\frac{1}{16}$	111.0	$\frac{3}{16}$	.0642	.01200	7
22 Novo	16	134	105	$\frac{1}{8}$x$\frac{1}{16}$	107.2	$\frac{1}{8}$	.0642	.00802	$12\frac{1}{2}$
23 Styrian	23	135	130	$\frac{1}{8}$x$\frac{1}{32}$	133.8	$\frac{1}{8}$	.0312	.00390	$4\frac{2}{3}$
24 "	23	136	130	"	134.3	$\frac{1}{8}$	.0312	.00390	$2\frac{1}{6}$
25 "	23	137	100	"	102.9	$\frac{1}{8}$	.0312	.00390	$17\frac{1}{2}$
26 Novo	23	138	100	"	106.3	$\frac{1}{8}$	.0312	.00390	$1\frac{1}{6}$
27 "	22	139	100	"	101.5	$\frac{1}{8}$	.0312	.00390	$6\frac{2}{3}$
28 Styrian	22	140	80	"	79.5	$\frac{1}{8}$	.0312	.00390	8
29 Jessop	31	141	50	$\frac{1}{8}$x$\frac{1}{16}$	53.3	$\frac{1}{8}$	.0642	.00802	$13\frac{1}{3}$
30 "	31	142	75	"	75.2	$\frac{1}{8}$	.0642	.00802	$14\frac{3}{4}$
31 "	32	143	85	"	85.0	$\frac{1}{8}$	.0642	.00802	$22\frac{1}{2}$

TABLE I—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Styrian..........	3.53	.107	43.60	1.320	Time up	100.00	114.5
2 "	2.92	.094	50.50	1.630	"	50.50	114.5
3 "	2.67	.169	24.20	1.530	"	12.90	114.5
4 "	2.36	.472	10.30	2.060	"	100.00	114.5
5 "	2.27	.310	9.82	1.340	"	100.00	114.5
6 "	1.51	.151	6.81	.681	"	100.00	114.5
7 "	.20	.135	25.90	1.730	"	100.00	114.5
8 "	.99	.124	12.20	1.530	"	100.00	114.5
9 "	.85	.107	6.74	.843	"	100.00	114.5
10 McInnes.........	1.51	.151	6.43	.643	"	2.03	342.0
11 "	1.70	.170	7.00	.700	Tool failed	0.00	342.0
12 "	1.70	.170	7.37	.737	Time up	4.07	342.0
13 Novo	4.77	.217	11.80	.539	"	6.52	342.0
14 "	3.72	.233	8.67	.542	"	6.93	342.0
15 "	4.31	.227	10.30	.541	"	4.90	342.0
16 Styrian..........	2.98	.221	7.26	.538	"	5.50	342.0
17 Novo	2.90	.223	6.99	.538	"	5.30	342.0
18 Styrian..........	4.54	.395	.....	.....	Tool failed	3.12	132.0
19 Novo	3.58	.398	.....	.....	"	0.10	132.0
20 McInnes.........	.40	.390	.....	.....	"	0.00	132.0
21 Styrian..........	4.16	.594	28.75	4.107	"	0.00	109.8
22 Novo	7.16	.573	32.20	2.580	Time up	5.09	109.8
23 Styrian..........	1.61	.347	7.08	1.520	Tool failed	0.00	122.2
24 "	.75	.349	3.28	1.520	"	0.00	122.2
25 "	4.67	.267	21.20	1.210	Time up	3.56	122.2
26 Novo	.....	.....	.....	.....	Tool failed	0.00	122.2
27 "	1.76	.264	9.12	1.370	"	0.00	167.5
28 Styrian..........	1.65	.206	8.72	1.090	"	0.00	167.5
29 Jessop	2.76	.282	17.20	1.290	Time up	100.00	124.5
30 "	5.92	.402	26.50	1.800	"	100.00	124.5
31 "	10.20	.454	45.60	2.030	"	18.30	124.5

TABLE II

Experiments with High-Speed Tool Steel on Cast Iron

Skin-Cut Trials

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended Speed	Intended Cut & Feed	Actual speed	Actual Cut	Actual Feed	Area of Sec. of cut	Duration of Trial
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Styrian .	28	1	45	$\frac{7}{32}$x$\frac{3}{128}$	45.2	$\frac{7}{32}$	.0232	.00507	9½
2 Styrian.	28	2	35	"	36.3	$\frac{7}{32}$	.0232	.00507	39
3 McInnes	29	12	45	$\frac{1}{4}$x$\frac{1}{64}$	46.2	$\frac{1}{4}$	.0156	.00390	30
4 McInnes	29	13	60	$\frac{1}{4}$x$\frac{1}{32}$	59.5	$\frac{1}{4}$	.0312	.00780	6½
5 McInnes	29	14	35	$\frac{1}{4}$x$\frac{1}{64}$	36.4	$\frac{1}{4}$	.0156	.00390	40
6 Styrian..	3	97	50	$\frac{3}{16}$x$\frac{1}{32}$	50.6	$\frac{3}{16}$	.0312	.00585	40
7 Styrian.	6&7	98	55	"	55.2	"	.0312	.00585	72½
8 Novo . . .	8	99	55	"	55.0	"	.0312	.00585	36
9 McInnes	9	100	55	"	57.4	"	.0312	.00585	35
10 Novo. . . .	10	101	55	"	55.5	"	.0312	.00585	35
11 McInnes	11	102	55	"	54.4	"	.0312	.00585	37
12 Poldi. . .	12&13	103	55	"	55.6	"	.0312	.00585	72
13 A. & W.	14	104	55	"	55.3	"	.0312	.00585	29½
14 A. & W.	4	105	55	"	56.0	"	.0312	.00585	37
15 Styrian..	5	106	70	"	67.9	"	.0312	.00585	30
16 Novo. . .	18	107	70	$\frac{1}{8}$x$\frac{1}{32}$	68.8	$\frac{1}{8}$	.0312	.00390	21
17 McInnes	19	108	70	"	68.5	"	.0312	.00390	8½
18 McInnes	19	109	70	"	68.5	"	.0312	.00390	10
19 Poldi. . .	20	110	70	"	68.0	"	.0312	.00390	19
20 Novo. . .	20	111	70	"	68.2	"	.0312	.00390	11
21 Styrian.	17	112	75	"	75.3	"	.0312	.00390	27
22 Novo. . .	26	113	75	"	75.2	"	.0312	.00390	27
23 McInnes	25	114	75	"	75.7	"	.0312	.00390	27
24 Poldi. . .	16	115	75	"	74.7	"	.0312	.00390	26½
25 A. & W.	24	116	75	"	73.9	"	.0312	.00390	27⅝
26 Styrian.	23	117	75	"	72.2	"	.0312	.00390	28
27 Poldi. . .	21	118	75	"	75.0	"	.0312	.00390	27
28 A. & W.	15	119	75	"	74.2	"	.0312	.00390	27
29 McInnes	22	120	75	"	73.8	"	.0312	.00390	19¼
30 Styrian.	22	121	75	"	72.5	"	.0312	.00390	8½
31 Jessop. .	32	122	45	$\frac{1}{4}$x$\frac{1}{32}$	46.1	$\frac{1}{4}$	.0312	.00780	28

TABLE II—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Styrian	0.83	.088	4.6	.488	Tool failed	0.00	114.5
2 Styrian	2.76	.070	14.4	.370	Time up	7.94	114.5
3 McInnes	1.81	.060	14.4	.480	"	6.12	195.0
4 McInnes	0.99	.155	7.1	1.105	Tool failed	5.23	195.0
5 McInnes	1.89	.047	14.7	.367	Time up	8.16	195.0
6 Styrian	5.24	.131	29.8	.746	"	100.00	94.2
7 Styrian	1.04	.143	57.2	.789	"	14.80	107.6
8 Novo	5.15	.143	23.3	.648	"	5.85	94.3
9 McInnes	5.21	.149	24.5	.702	"	5.70	138.6
10 Novo	5.04	.144	33.5	.958	"	14.30	106.8
11 McInnes	5.22	.141	30.0	.812	"	10.00	109.3
12 Poldi	10.40	.144	67.7	.941	"	17.85	103.3
13 A. & W	4.25	.144	29.8	1.012	"	24.00	117.2
14 A. & W	5.36	.145	35.6	.964	"	15.00	109.2
15 Styrian	5.28	.176	34.2	1.140	"	12.20	102.0
16 Novo	3.76	.179	30.8	1.470	"	4.28	107.0
17 McInnes	1.51	.178	.....	.....	Tool failed	0.00	117.2
18 McInnes	1.78	.178	.....	.....	Time up	8.13	117.2
19 Poldi	3.36	.177	21.0	1.110	Tool failed	0.00	113.9
20 Novo	1.95	.177	12.1	1.110	Time up	2.23	113.9
21 Styrian	5.29	.196	24.4	.903	"	22.00	90.3
22 Novo	5.26	.195	19.0	.704	"	7.33	95.9
23 McInnes	5.32	.197	23.0	.852	"	11.00	102.4
24 Poldi	5.14	.194	22.5	.850	"	10.80	109.8
25 A. & W	5.34	.192	24.6	.887	"	11.35	111.2
26 Styrian	5.23	.187	22.6	.808	"	7.61	122.2
27 Poldi	5.26	.195	19.1	.708	"	5.50	124.8
28 A. & W	5.21	.193	28.4	1.050	"	22.00	107.0
29 McInnes	3.70	.192	14.5	.756	Tool failed	00.00	167.5
30 Styrian	1.60	.188	.....	.....	Time up	3.46	167.5
31 Jessop	3.36	.120	27.5	.982	"	22.80	123.2

TABLE III

Experiments with High-Speed Tool Steel on Cast Iron

Endurance Trials

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended Speed	Intended Cut & Feed	Actual Speed	Actual Cut	Actual Feed	Area of Sec. of cut	Duration of Trial
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Novo. ..	29	15	50	$\frac{1}{2}$x$\frac{1}{64}$	47.6	$\frac{1}{2}$	.0156	.00780	68
2 Styrian.	30	17	50	"	48.3	$\frac{1}{2}$	.0156	.00780	161
3 McInnes	30	18	50	"	52.4	$\frac{1}{2}$	.0156	.00780	120
4 Jessop..	31	124	75	$\frac{1}{4}$x$\frac{1}{32}$	76.9	$\frac{1}{4}$	.0312	.00780	51
5 Novo. ..	29	16	40	$\frac{1}{2}$x$\frac{1}{32}$	37.6	$\frac{1}{2}$	.0312	.01560	107$\frac{1}{2}$
6 McInnes	27	19	75	$\frac{1}{8}$x$\frac{1}{32}$	77.8	$\frac{1}{8}$	.0312	.00390	181
7 Novo. ..	27	20	75	"	75.5	$\frac{1}{8}$	.0312	.00390	88$\frac{1}{12}$
8 Styrian.	3	36	65	"	63.6	$\frac{1}{8}$	.0312	.00390	195$\frac{1}{2}$
9 McInnes	3	37	65	"	67.7	$\frac{1}{8}$	.0312	.00390	181$\frac{1}{2}$
10 Novo. ..	3	38	65	"	67.1	$\frac{1}{8}$	.0312	.00390	40$\frac{1}{2}$
11 Styrian.	1	21	30	$\frac{1}{8}$x$\frac{1}{16}$	28.0	$\frac{1}{8}$	.0642	.00802	98$\frac{1}{2}$
12 Novo. ..	1	22	30	"	27.7	$\frac{1}{8}$	.0642	.00802	97$\frac{1}{4}$
13 Novo. ..	2	34	50	"	51.1	$\frac{1}{8}$	.0642	.00802	153$\frac{1}{2}$
14 Styrian.	2	35	50	"	53.2	$\frac{1}{8}$	.0642	.00802	127
15 Jessop..	31	123	75	"	74.5	$\frac{1}{8}$	.0642	.00802	47$\frac{1}{3}$
16 Rex.. ..	32	126	80	"	80.4	$\frac{1}{8}$	.0642	.00802	55
17 Styrian..	12	45	85	$\frac{1}{8}$x$\frac{3}{32}$	88.7	$\frac{1}{8}$	.0952	.01190	49$\frac{3}{4}$
18 McInnes	14	47	90	"	92.4	$\frac{1}{8}$	.0952	.01190	15$\frac{1}{2}$
19 Novo....	13	46	95	"	97.7	$\frac{1}{8}$	.0952	.01190	48$\frac{1}{6}$
20 Poldi....	14	48	105	"	105.2	$\frac{1}{8}$	.0952	.01190	17$\frac{1}{3}$
21 A. & W.	14	49	115	"	113.6	$\frac{1}{8}$	.0952	.01190	17$\frac{1}{2}$
22 Styrian..	1	26	35	$\frac{1}{16}$x$\frac{1}{16}$	38.7	$\frac{1}{16}$	.0642	.00401	88
23 McInnes	1	32	35	"	36.1	$\frac{1}{16}$	.0642	.00401	64$\frac{1}{2}$
24 Styrian..	1	33	35	"	36.6	$\frac{1}{16}$	.0642	.00401	58$\frac{1}{2}$
25 Rex.....	32	125	85	"	84.5	$\frac{1}{16}$	.0642	.00401	62$\frac{1}{2}$
26 Styrian..	6& 7	39	75	$\frac{1}{16}$x$\frac{3}{32}$	76.6	$\frac{1}{16}$	.0952	.00595	125
27 Novo. ..	7& 8	40	75	"	74.3	$\frac{1}{16}$	.0952	.00595	119$\frac{1}{2}$
28 McInnes	8& 9	41	75	"	77.5	$\frac{1}{16}$	.0952	.00595	130
29 Poldi...	9& 10	42	75	"	77.4	$\frac{1}{16}$	.0952	.00595	128
30 A. & W.	10& 11	43	75	"	75.0	$\frac{1}{16}$	.0952	.00595	122$\frac{1}{2}$
31 Mushet.	11	44	75	"	74.6	$\frac{1}{16}$	.0952	.00595	42$\frac{1}{2}$

TABLE III—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Novo............	4.2	.062	71.9	1.058	Time up	27.6	195.0
2 Styrian..........	10.1	.062	182.0	1.132	"	100.0	124.2
3 McInnes.........	8.2	.068	130.0	1.087	"	100.0	124.2
4 Jessop...........	10.2	.200	89.6	1.756	"	20.7	124.5
5 Novo............	10.5	.097	182.0	1.695	"	29.2	195.0
6 McInnes.........	36.6	.202	161.0	.892	"	100.0	132.0
7 Novo............	17.4	.196	77.8	.875	"	100.0	132.0
8 Styrian..........	32.2	.165	154.0	.791	"	53.1	94.2
9 McInnes.........	31.9	.176	145.0	.798	"	36.9	94.2
10 Novo...........	7.0	.174	30.7	.758	"	100.0	94.2
11 Styrian.........	14.7	.149	63.2	.642	"	40.0	342.0
12 Novo...........	14.4	.148	67.6	.695	"	26.3	342.0
13 Novo...........	41.9	.273	189.0	1.230	"	28.6	175.2
14 Styrian.........	36.1	.284	165.0	1.300	"	42.8	175.2
15 Jessop..........	18.8	.398	86.2	1.820	"	9.6	124.5
16 Rex.............	23.6	.430	106.0	1.930	Tool failed	9.6	123.2
17 Styrian.........	34.9	.702	163.0	3.270	Time up	20.3	100.0
18 McInnes........	11.3	.732	.....	.....	Tool failed	2.5	117.2
19 Novo...........	37.3	.774	167.0	3.480	Time up	13.0	106.6
20 Poldi...........	14.4	.834	61.9	3.570	Tool failed	0.0	117.2
21 A. & W.........	15.8	.902	64.9	3.710	"	3.8	117.2
22 Styrian.........	18.2	.207	42.0	.477	Time up	17.1	342.0
23 McInnes........	12.4	.193	38.2	.593	"	17.5	342.0
24 Styrian.........	11.4	.195	26.8	.458	"	11.9	342.0
25 Rex.............	28.2	.452	61.5	.984	"	17.0	123.2
26 Styrian.........	75.0	.600	175.0	1.400	"	50.9	107.6
27 Novo...........	69.5	.582	170.0	1.420	"	32.4	90.4
28 McInnes........	79.8	.614	191.0	1.470	"	27.4	116.4
29 Poldi...........	78.6	.614	184.0	1.440	"	34.7	122.7
30 A. & W.........	72.9	.595	169.9	1.380	"	23.0	108.0
31 Mushet..........	25.1	.591	60.3	1.420	"	100.	109.3

TABLE IV

Experiments with High-Speed Tool Steel on Cast Iron

Trials to Determine Variation of Durability with Cutting Speed

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended. Speed	Intended. Cut & Feed	Actual Speed	Actual Cut	Actual Feed	Area of Sec. of cut	Duration of Trial
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Styrian	18	59	90	$\frac{1}{16}$x$\frac{3}{32}$	91.5	$\frac{1}{16}$	.0952	.00595	44
2 “	18	60	100	“	102.5	$\frac{1}{16}$	.0952	.00595	$28\frac{1}{2}$
3 “	18	61	110	“	110.6	$\frac{1}{16}$	.0952	.00595	$43\frac{1}{2}$
4 “	18	62	120	“	120.6	$\frac{1}{16}$	.0952	.00595	$41\frac{1}{3}$
5 Mushet	5	58	90	$\frac{1}{8}$x$\frac{1}{32}$	91.6	$\frac{1}{8}$	.0312	.00390	$12\frac{1}{4}$
6 McInnes	5	54	95	“	95.3	$\frac{1}{8}$	.0312	.00390	62
7 “	5	55	100	“	100.3	$\frac{1}{8}$	.0312	.00390	$61\frac{1}{2}$
8 “	5	56	110	“	110.9	$\frac{1}{8}$	.0312	.00390	$62\frac{1}{3}$
9 “	5	57	120	“	123.4	$\frac{1}{8}$	.0312	.00390	31
10 Novo	4	50	85	$\frac{1}{8}$x$\frac{1}{16}$	86.1	$\frac{1}{8}$	.0642	.00800	29
11 “	4	51	95	“	98.7	$\frac{1}{8}$	.0642	.00800	$27\frac{1}{2}$
12 “	4	52	105	“	105.2	$\frac{1}{8}$	.0642	.00800	30
13 “	4	53	115	“	114.9	$\frac{1}{8}$	.0642	.00800	$31\frac{1}{2}$
14 Poldi	19	63	105	$\frac{3}{16}$x$\frac{1}{16}$	106.8	$\frac{3}{16}$	.0642	.01200	$22\frac{1}{2}$
15 “	19	64	115	“	116.1	$\frac{3}{16}$	.0642	.01200	$21\frac{5}{6}$
16 “	19	65	125	“	125.7	$\frac{3}{16}$	.0642	.01200	22
17 A. & W.	20	66	110	$\frac{1}{4}$x$\frac{1}{16}$	109.3	$\frac{1}{4}$	.0642	.01600	$16\frac{1}{2}$
18 “	20	67	120	“	120.0	$\frac{1}{4}$	.0642	.01600	$18\frac{1}{2}$
19 “	20	68	130	“	130.4	$\frac{1}{4}$	.0642	.01600	$19\frac{1}{4}$

TABLE IV—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Styrian..........	31.9	.726	70.0	1.59	Time up	12.00	107.0
2 "	23.1	.812	48.2	1.69	Tool failed	7.76	107.0
3 "	38.1	.877	87.9	2.02	Time up	11.80	107.0
4 "	39.5	.956	96.6	2.34	"	5.50	107.0
5 Mushet..........	2.9	.238	12.1	.99	Tool failed	0.00	102.0
6 McInnes..........	15.3	.247	65.7	1.06	Time up	50.57	102.0
7 "	16.0	.261	71.3	1.16	"	25.60	102.0
8 "	17.9	.288	78.5	1.26	"	13.00	102.0
9 "	9.9	.321	43.7	1.41	Tool failed	6.37	102.0
10 Novo	13.3	.460	61.8	2.13	Time up	7.53	109.2
11 "	14.5	.527	66.0	2.40	"	5.63	109.2
12 "	16.9	.562	83.1	2.77	"	12.20	109.2
13 "	19.3	.614	88.8	2.82	"	3.31	109.2
14 Poldi	12.9	.572	85.7	3.81	"	13.90	117.2
15 "	13 5	.622	92.6	4.25	"	35.50	117.2
16 "	14.8	.672	102.0	4.64	"	100.00	117.2
17 A. & W..........	9.6	.584	87.1	5.28	"	13.40	113.9
18 "	11.9	.642	106.0	5.72	"	100.00	113.9
19 "	13.4	.697	118.0	6.16	"	15.70	113.9

TABLE V

Experiments with High-Speed Tool Steel on Cast Iron

Trials to Determine Variation of Durability with Hardness

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended		Actual	Actual		Area of sec. of cut	Duration of Trial
			Speed	Cut & Feed	speed	Cut	Feed		
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Novo...	22	94	50	$\frac{1}{8}\times\frac{1}{32}$	50.9	$\frac{1}{8}$	.0312	.00390	83
2 Poldi...	22	96	75	“	75.1	$\frac{1}{8}$	.0312	.00390	$88\frac{1}{2}$
3 Styrian.	23	85	75	“	75.2	$\frac{1}{8}$	.0312	.00390	$38\frac{1}{2}$
4 Novo...	15	91	100	“	100.3	$\frac{1}{8}$	.0312	.00390	$37\frac{3}{4}$
5 A. & W.	21	88	100	“	101.5	$\frac{1}{8}$	.0312	.00390	38
6 McInnes	17	70	100	“	101.9	$\frac{1}{8}$	.0312	.00390	$36\frac{3}{4}$
7 Poldi...	26	73	125	“	125.8	$\frac{1}{8}$	.0312	.00390	$30\frac{1}{2}$
8 A. & W.	16	79	130	“	130.0	$\frac{1}{8}$	.0312	.00390	$29\frac{5}{6}$
9 Styrian.	25	76	130	“	131.2	$\frac{1}{8}$	.0312	.00390	$29\frac{3}{4}$
10 Novo...	24	82	130	“	132.0	$\frac{1}{8}$	.0312	.00390	$29\frac{3}{4}$
11 Poldi...	22	95	50	$\frac{1}{8}\times\frac{1}{16}$	50.4	$\frac{1}{8}$	.0642	.00802	$33\frac{3}{4}$
12 A. & W.	23	86	70	“	70.9	$\frac{1}{8}$	.0642	.00802	$23\frac{5}{6}$
13 A. & W.	15	92	95	“	95.0	$\frac{1}{8}$	.0642	.00802	28
14 McInnes	21	89	95	“	95.2	$\frac{1}{8}$	.0642	.00802	$20\frac{1}{2}$
15 Styrian..	17	71	95	“	95.2	$\frac{1}{8}$	.0642	.00802	27
16 Poldi...	16	80	120	“	120.0	$\frac{1}{8}$	.0642	.00802	9
17 Novo...	25	77	120	“	121.2	$\frac{1}{8}$	.0642	.00802	21
18 McInnes	24	83	120	“	122.7	$\frac{1}{8}$	.0642	.00802	$21\frac{1}{2}$
19 A. & W.	26	74	140	“	143.4	$\frac{1}{8}$	.0642	.00802	$18\frac{1}{2}$
20 Novo...	23	87	65	$\frac{3}{16}\times\frac{1}{16}$	65.5	$\frac{3}{16}$	.0642	.01200	33
21 Styrian..	21	90	85	“	85.2	$\frac{3}{16}$	.0642	.01200	$32\frac{1}{6}$
22 Poldi...	15	93	85	“	86.2	$\frac{3}{16}$	.0642	.01200	$25\frac{3}{4}$
23 Novo...	17	72	85	“	88.8	$\frac{3}{16}$	.0642	.01200	24
24 McInnes	26	75	100	“	101.1	$\frac{3}{16}$	.0642	.01200	22
25 Styrian..	16	81	110	“	109.8	$\frac{3}{16}$	.0642	.01200	$13\frac{1}{4}$
26 A. & W.	24	84	110	“	110.6	$\frac{3}{16}$	.0642	.01200	16
27 Poldi...	25	78	110	“	111.5	$\frac{3}{16}$	.0642	.01200	21
28 Rex....	32	127	70	“	72.2	$\frac{3}{16}$	.0642	.01200	29

TABLE V—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Novo	10.9	.132	55.4	.668	Time up	67.6	167.5
2 Poldi	17.2	.195	75.9	.858	"	68.1	167.5
3 Styrian	7.5	.195	35.8	.929	"	15.7	122.2
4 Novo	9.9	.262	45.2	1.200	"	100.0	132.0
5 A. & W.	10.0	.264	46.0	1.210	"	31.0	124.8
6 McInnes	9.6	.264	44.8	1.220	"	60.0	90.3
7 Poldi	9.9	.327	48.2	1.580	"	24.8	95.9
8 A. & W.	10.1	.338	44.1	1.480	"	12.2	109.8
9 Styrian	10.1	.341	45.7	1.540	"	100.0	102.4
10 Novo	10.2	.343	47.5	1.600	"	12.1	111.2
11 Poldi	9.0	.269	41.1	1.220	"	27.5	167.5
12 A. & W.	9.0	.379	41.2	1.730	"	38.8	122.2
13 A. & W.	44.2	.508	59.1	2.110	"	100.0	132.0
14 McInnes	10.4	.509	43.7	2.130	Tool failed	.0	124.8
15 Styrian	13.7	.509	58.9	2.180	Time up	100.0	90.3
16 Poldi	5.7	.642	24.1	2.680	Tool failed	.0	109.8
17 Novo	13.6	.649	61.7	2.940	Time up	100.0	102.4
18 McInnes	14.1	.657	65.6	3.050	"	35.0	111.2
19 A. & W.	14.2	.767	64.4	3.480	"	15.1	95.9
20 Novo	11.5	.350	79.2	2.400	"	65.5	122.2
21 Styrian	14.6	.455	98.7	3.070	"	13.1	124.8
22 Poldi	18.5	.461	73.5	2.860	"	10.4	132.0
23 Novo	11.4	.475	77.3	3.220	"	100 0	90.3
24 McInnes	11.9	.541	78.5	3.570	"	35.8	95.9
25 Styrian	7.7	.588	50.8	3.850	"	3.6	109.8
26 A. & W.	9.5	.592	64.3	4.020	"	26.0	111.2
27 Poldi	12.5	.597	82.1	3.910	"	100.0	102.4
28 Rex	11.2	.386	72.3	2.490	"	4.7	123.2

TABLE VI

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

PRELIMINARY TRIALS

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel.	Test Piece No.	Trial No.	Total output of Motor	Required to drive lathe and countershaft	Net required for cutting	Actual cutting speed
					Col. (4) — (5)	Ft./Min.
1 Styrian.........	28	3	2.52	.65	1.87	54.8
2 "	"	4	2.78	.67	2.11	36.2
3 "	"	5	2.30	.63	1.67	32.5
4 "	"	6	3.05	.70	2.35	60.5
5 "	"	7	2.29	.63	1.66	59.6
6 "	"	8	1.29	.53	.76	58.0
7 "	"	9	3.08	.70	2.38	52.1
8 "	"	10	2.42	.64	1.78	47.6
9 "	"	11	1.46	.55	.91	41.2
10 McInnes........	1	23	1.83	.58	1.25	28.4
11 "	"	24	1.90	.59	1.31	31.8
12 "	"	25	1.87	.59	1.28	31.9
13 Novo...........	"	27	1.48	.55	.93	40.7
14 "	"	28	1.67	.57	1.10	43.7
15 "	"	29	1.41	.54	.87	42.5
16 Styrian.........	"	30	1.52	.55	.97	41.3
17 Novo...........	"	31	1.42	.54	.88	41.7
18 Styrian.........	27	130	3.06	.67	2.39	152.1
19 Novo...........	"	131	2.83	.55	2.28	153.1
20 McInnes........	"	132	......	...	.....	150.0
21 Styrian.........	16	133	4.89	.89	4.00	111.0
22 Novo...........	"	134	3.12	.68	2.44	107.2
23 Styrian.........	23	135	2.74	.64	2.10	133.8
24 "	"	136	2.69	.63	2.06	134.3
25 "	"	137	2.45	.60	1.85	102.9
26 Novo...........	"	138	......	...	.....	106.3
27 "	22	139	2.43	.60	1.83	101.5
28 Styrian.........	"	140	2.50	.65	1.85	79.5
29 Jessop..........	31	141	2.50	.65	1.85	53.3
30 "	"	142	2.82	.64	2.18	75.2
31 "	32	143	2.82	.64	2.18	85.0

TABLE VI—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting force on point of Tool.		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total calculated	Per Sq. In. Area of cut			
	Lbs.	Lbs.	Ins.	Sq. In.	
1 Styrian.....	1126	129300	$\frac{3}{8} \times \frac{3}{128}$	.00870	114.5
2 "	1923	123200	$\frac{1}{2} \times \frac{1}{32}$	.01560	114.5
3 "	1696	106000	$\frac{1}{4} \times \frac{1}{16}$	.01600	114.5
4 "	1282	107800	$\frac{1}{8} \times \frac{3}{32}$	.01190	114.5
5 "	920	114800	$\frac{1}{8} \times \frac{1}{16}$	.00802	114.5
6 "	432	110800	$\frac{1}{8} \times \frac{1}{32}$	.00390	114.1
7 "	1508	130000	$\frac{3}{8} \times \frac{1}{32}$	.01160	114.5
8 "	1235	106500	$\frac{3}{8} \times \frac{1}{32}$	.01160	114.5
9 "	728	93400	$\frac{1}{4} \times \frac{1}{32}$	.00780	114.5
10 McInnes......	1451	181000	$\frac{1}{8} \times \frac{1}{16}$	.00802	342.0
11 "	1360	169800	"	.00802	342.0
12 "	1325	165300	"	.00802	342.0
13 Novo.........	754	188000	$\frac{1}{16} \times \frac{1}{16}$	.00401	342.0
14 "	832	207000	"	.00401	342.0
15 "	675	168200	"	.00401	342.0
16 Styrian.......	773	192500	"	.00401	342.0
17 Novo.........	697	173500	"	.00401	342.0
18 Styrian.......	519	133000	$\frac{1}{8} \times \frac{1}{32}$	.00390	132.0
19 Novo.........	492	126000	"	.00390	132.0
20 McInnes......	....	......	"	.00390	132.0
21 Styrian.......	1189	99100	$\frac{3}{16} \times \frac{1}{16}$	.01200	109.8
22 Novo.........	752	93800	$\frac{1}{8} \times \frac{1}{16}$	.00802	109.8
23 Styrian.......	518	132800	$\frac{1}{8} \times \frac{1}{32}$	.00390	122.2
24 "	507	130000	"	.00390	122.2
25 "	593	152000	"	.00390	122.2
26 Novo.........	....	......	"	.00390	122.2
27 "	595	152500	"	.00390	167.5
28 Styrian.......	768	196800	"	.00390	167.5
29 Jessop........	1145	142800	$\frac{1}{8} \times \frac{1}{16}$	.00802	124.5
30 "	958	119300	"	.00802	124.5
31 "	847	105600	"	.00802	124.5

TABLE VII

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

SKIN CUT TRIALS

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Total Output of Motor	Required to drive lathe and countershaft	Net Required for Cutting	Actual Cutting Speed
					Col. (4) − (5)	Ft./Min.
1 Styrian	28	1	1.22	.52	0.70	45.2
2 Styrian	28	2	0.82	.49	0.33	36.3
3 McInnes	29	12	1.47	.55	0.92	46.2
4 McInnes	29	13	2.53	.65	1.88	59.5
5 McInnes	29	14	1.14	.52	0.62	36.4
6 Styrian	3	97	1.38	.54	0.84	50.6
7 Styrian	6 & 7	98	1.67	.57	1.10	55.2
8 Novo	8	99	1.48	.55	0.93	55.0
9 McInnes	9	100	1.74	.57	1.17	57.4
10 Novo	10	101	1.96	.60	1.36	55.5
11 McInnes	11	102	1.74	.57	1.17	54.4
12 Poldi	12 & 13	103	1.86	.59	1.27	55.6
13 A & W	14	104	1.38	.54	0.84	55.3
14 A & W	4	105	1.82	.58	1.24	56.0
15 Styrian	5	106	2.00	.60	1.40	67.9
16 Novo	18	107	2.12	.61	1.51	68.8
17 McInnes	19	108	2.29	.63	1.66	68.5
18 McInnes	19	109	2.29	.63	1.66	68.5
19 Poldi	20	110	2.50	.65	1.85	68.0
20 Novo	20	111	2.41	.64	1.77	68.2
21 Styrian	17	112	1.88	.59	1.29	75.3
22 Novo	26	113	1.88	.59	1.29	75.2
23 McInnes	25	114	1.78	.58	1.20	75.7
24 Poldi	16	115	1.83	.58	1.25	74.7
25 A & W	24	116	1.96	.60	1.36	73.9
26 Styrian	23	117	1.84	.58	1.26	72.2
27 Poldi	21	118	1.85	.58	1.27	75.0
28 A & W	15	119	2.19	.62	1.57	74.2
29 McInnes	22	120	2.02	.60	1.42	73.8
30 Styrian	22	121	1.76	.58	1.18	72.5
31 Jessop	32	122	2.00	.60	1.40	46.1

TABLE VII—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total Calculated	Per Sq. In. Area of Cut			
	Lbs.	Lbs.	Ins.	Sq. In.	
1 Styrian.......	511	101000	$\frac{7}{32}$x$\frac{3}{128}$	.00507	114.5
2 Styrian.......	300	59300	"	.00507	114.5
3 McInnes......	658	168500	$\frac{1}{4}$x$\frac{1}{64}$	.00390	195.0
4 McInnes......	1042	133800	$\frac{1}{4}$x$\frac{1}{32}$	.00780	195.0
5 McInnes......	562	144000	$\frac{1}{4}$x$\frac{1}{64}$	.00390	195.0
6 Styrian.......	548	93800	$\frac{3}{16}$x$\frac{1}{32}$	.00585	94.2
7 Styrian.......	658	112500	"	.00585	107.6
8 Novo.........	558	95500	"	.00585	94.3
9 McInnes......	673	115000	"	.00585	138.6
10 Novo.........	809	138300	"	.00585	106.8
11 McInnes......	710	121300	"	.00585	109.3
12 Poldi.........	754	129000	"	.00585	103.3
13 A & W	502	85800	"	.00585	117.2
14 A & W	732	125000	"	.00585	109.2
15 Styrian.......	682	116300	"	.00585	102.0
16 Novo.........	725	185800	$\frac{1}{8}$x$\frac{1}{32}$	.00390	107.0
17 McInnes......	800	205000	"	.00390	117.2
18 McInnes......	800	205000	"	.00390	117.2
19 Poldi.........	899	230000	"	.00390	113.9
20 Novo.........	858	219600	"	.00390	113.9
21 Styrian.......	565	145000	"	.00390	90.3
22 Novo.........	567	145200	"	.00390	95.9
23 McInnes	524	134300	"	.00390	102.4
24 Poldi.........	553	141800	"	.00390	109.8
25 A & W	608	155800	"	00390	111.2
26 Styrian.......	577	147800	"	.00390	122.2
27 Poldi.........	559	143200	"	.00390	124.8
28 A & W	699	179000	"	.00390	107.0
29 McInnes......	636	163000	"	.00390	167.5
30 Styrian.......	538	137800	"	.00390	167.5
31 Jessop	1001	128500	$\frac{1}{4}$x$\frac{1}{32}$	.00780	123.2

TABLE VIII

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

ENDURANCE TRIALS

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Total Output of Motor	Required to drive lathe and countershaft	Net Required for Cutting	Actual Cutting Speed
					Col. (4) − (5)	Ft./Min.
1 Novo...........	29	15	2.83	.68	2.15	47.6
2 Styrian.........	30	17	2.52	.65	1.87	48.3
3 McInnes........	30	18	2.31	.63	1.68	52.4
4 Jessop...	31	124	3.10	.68	2.42	76.9
5 Novo...........	29	16	3.58	.75	2.83	37.6
6 McInnes........	27	19	1.57	.56	1.01	77.8
7 Novo...........	27	20	1.49	.49	1.00	75.5
8 Styrian.........	3	36	1.34	.54	0.80	63.6
9 McInnes........	3	37	1.33	.47	0.86	67.7
10 Novo...........	3	38	1.27	.47	0.80	67.1
11 Styrian.........	1	21	1.56	.56	1.00	28.0
12 Novo...........	1	22	1.66	.56	1.10	27.7
13 Novo...........	2	34	2.13	.61	1.52	51.1
14 Styrian.........	2	35	1.78	.58	1.20	53.2
15 Jessop..........	31	123	2.98	.66	2.32	74.5
16 Rex.............	32	126	3.05	.67	2.38	80.4
17 Styrian.........	12	45	3.16	.68	2.48	88.7
18 McInnes........	14	47	3.53	.73	2.80	92.4
19 Novo...........	13	46	3.67	.74	2.93	97.7
20 Poldi	14	48	4.49	.83	3.66	105.2
21 A. & W.........	14	49	4.83	.87	3.96	113.6
22 Styrian.........	1	26	1.19	.52	0.67	38.7
23 McInnes........	1	32	1.24	.53	0.71	36.1
24 Styrian.........	1	33	1.29	.47	0.82	36.6
25 Rex.............	32	125	2.03	.57	1.46	84.5
26 Styrian..... ...	6 & 7	39	1.89	.57	1.32	76.6
27 Novo..........	7 & 8	40	1.56	.50	1.06	74.3
28 McInnes........	8 & 9	41	1.92	.59	1.33	77.5
29 Poldi...........	9 & 10	42	2.04	.60	1.44	77.4
30 A. & W.........	10 & 11	43	1.96	.54	1.42	75.0
31 Mushet.........	11	44	1.79	.53	1.26	74.6

TABLE VIII—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total Calculated	Per Sq. In. Area of Cut			
	Lbs.	Lbs.	Ins.	Sq. Ins.	
1 Novo.........	1492	191500	$\frac{1}{2} \times \frac{1}{64}$	.00780	195.0
2 Styrian.......	1275	163500	"	.00780	124.2
3 McInnes......	1059	135800	"	.00780	124.2
4 Jessop........	1040	133300	$\frac{1}{4} \times \frac{1}{32}$	.00780	124.5
5 Novo.........	2482	159100	$\frac{1}{2} \times \frac{1}{32}$	.01560	195.0
6 McInnes......	428	109700	$\frac{1}{8} \times \frac{1}{32}$	.00390	132.0
7 Novo.........	437	112000	"	.00390	132.0
8 Styrian.......	415	106400	"	.00390	94.2
9 McInnes......	419	107300	"	.00390	94.2
10 Novo.........	394	101000	"	.00390	94.2
11 Styrian.......	1179	147000	$\frac{1}{8} \times \frac{1}{16}$	.00802	342.0
12 Novo.........	1310	163500	"	.00802	342.0
13 Novo.........	982	122500	"	.00802	175.2
14 Styrian......	745	93000	"	.00802	175.2
15 Jessop........	1029	128300	"	.00802	124.5
16 Rex..........	978	122000	"	.00802	123.2
17 Styrian.......	924	77900	$\frac{1}{8} \times \frac{3}{32}$	.01190	100.0
18 McInnes......	1000	84000	"	.01190	117.2
19 Novo.........	1010	84900	"	.01190	106.6
20 Poldi..... ...	1148	96500	"	.01190	117.2
21 A. & W.......	1151	96800	"	.01190	117.2
22 Styrian.......	571	142300	$\frac{1}{16} \times \frac{1}{16}$	.00401	342.0
23 McInnes......	649	161600	"	.00401	342.0
24 Styrian.......	739	184000	"	.00401	342.0
25 Rex..........	570	142000	"	.00401	123.2
26 Styrian.......	569	95700	$\frac{1}{16} \times \frac{3}{32}$	.00595	107.6
27 Novo.........	471	79200	"	.00595	90.4
28 McInnes......	567	95300	"	.00595	116.4
29 Poldi.........	615	103200	"	.00595	122.7
30 A. & W.......	625	105000	"	.00595	108.0
31 Mushet.......	557	93800	"	.00595	109.3

TABLE IX

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

TRIALS TO DETERMINE VARIATION OF DURABILITY WITH CUTTING SPEED

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Total Output of Motor	Required to drive lathe and countershaft	Net Required for Cutting	Actual Cutting Speed
					Col. (4)—(5)	Ft./Min.
1 Styrian.........	18	59	2.38	.59	1.79	91.5
2 Styrian.........	18	60	2.71	.63	2.08	102.5
3 Styrian.........	18	61	2.84	.65	2.19	110.6
4 Styrian........	18	62	3.08	.67	2.41	120.6
5 Mushet.........	5	58	1.77	.52	1.25	91.6
6 McInnes........	5	54	1.58	.50	1.08	95.3
7 McInnes........	5	55	1.78	.52	1.26	100.3
8 McInnes........	5	56	2.16	.59	1.57	110.9
9 McInnes........	5	57	2.19	.57	1.62	123.4
10 Novo...........	4	50	2.61	.62	1.99	86.1
11 Novo...........	4	51	2.92	.66	2.26	98.7
12 Novo...........	4	52	3.14	.68	2.46	105.2
13 Novo...........	4	53	3.76	.75	3.01	114.9
14 Poldi...........	19	63	4.48	.83	3.65	106.8
15 Poldi...........	19	64	5.06	.90	4.16	116.1
16 Poldi...........	19	65	5.20	.92	4.28	125.7
17 A. & W.........	20	66	6.50	1.07	5.43	109.3
18 A. & W.........	20	67	5.98	1.01	4.97	120.0
19 A. & W.........	20	68	6.04	1.01	5.03	130.4

TABLE IX—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total Calculated	Per Sq. In. Area of Cut			
	Lbs.	Lbs.	Ins.	Sq. Ins.	
1 Styrian.......	647	108800	$\frac{1}{16} \times \frac{3}{32}$	.00595	107.0
2 Styrian.......	670	112600	"	.00595	107.0
3 Styrian.......	653	109800	"	.00595	107.0
4 Styrian.......	661	111000	"	.00595	107.0
5 Mushet.......	450	115400	$\frac{1}{8} \times \frac{1}{32}$	.00390	102.0
6 McInnes	374	96000	"	.00390	102.0
7 McInnes......	414	106100	"	.00390	102.0
8 McInnes......	468	120000	"	.00390	102.0
9 McInnes......	433	111100	"	.00390	102.0
10 Novo.........	763	95300	$\frac{1}{8} \times \frac{1}{16}$	.00802	109.2
11 Novo.........	757	94400	"	.00802	109.2
12 Novo.........	772	96300	"	.00802	109.2
13 Novo.........	866	108000	"	.00802	109.2
14 Poldi.........	1128	94000	$\frac{3}{16} \times \frac{1}{16}$	.01200	117.2
15 Poldi.........	1182	98500	"	.01200	117.2
16 Poldi.........	1124	93750	"	.01200	117.2
17 A. & W.......	1640	102500	$\frac{1}{4} \times \frac{1}{16}$	.01600	113.9
18 A. & W.......	1366	85500	"	.01600	113.9
19 A. & W......	1273	79600	"	.01600	113.9

TABLE X

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

TRIALS TO DETERMINE VARIATION OF DURABILITY WITH HARDNESS

1	2	3	4	5	6	7
Name of Brand of Tool Steel.	Test Piece No.	Trial No.	Horse-Power: Total output of Motor	Horse-Power: Required to drive lathe and countershaft	Horse-Power: Net required for cutting	Actual cutting speed
					Col. (4) — (5)	Ft./Min.
1 Novo	22	94	1.57	.56	1.01	50.9
2 Poldi	22	96	2.03	.55	1.48	75.1
3 Styrian	23	85	2.08	.56	1.52	75.2
4 Novo	15	91	1.88	.54	1.34	100.3
5 A. & W.	21	88	2.18	.57	1.61	101.5
6 McInnes	17	70	1.87	.53	1.34	101.9
7 Poldi	26	73	2.51	.61	1.90	125.8
8 A. & W.	16	79	2.38	.59	1.79	130.0
9 Styrian	25	76	2.26	.58	1.68	131.2
10 Novo	24	82	2.54	.61	1.93	132.0
11 Poldi	22	95	2.44	.64	1.80	50.4
12 A. & W.	23	86	2.73	.63	2.10	70.9
13 A. & W.	15	92	2.62	.62	2.00	95.0
14 McInnes	21	89	4.07	.80	3.27	95.2
15 Styrian	17	71	2.65	.62	2.03	95.2
16 Poldi	16	80	3.88	.77	3.11	120.0
17 Novo	25	77	3.33	.70	2.63	121.2
18 McInnes	24	83	3.27	.70	2.57	122.7
19 A. & W.	26	74	3.83	.76	3.07	143.4
20 Novo	23	87	3.55	.75	2.80	65.5
21 Styrian	21	90	4.05	.79	3.26	85.2
22 Poldi	15	93	3.96	.78	3.18	86.2
23 Novo	17	72	3.36	.70	2.66	88.8
24 McInnes	26	75	3.68	.74	2.94	101.1
25 Styrian	16	81	4.58	.84	3.74	109.8
26 A. & W.	24	84	4.02	.78	3.24	110.6
27 Poldi	25	78	4.22	.80	3.42	111.5
28 Rex	32	127	3.50	.72	2.78	72.2

TABLE X—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total Calculated	Per Sq. In. Area of Cut			
	Lbs.	Lbs.	Ins.	Sq. Ins.	
1 Novo	655	168000	$\frac{1}{8} \times \frac{1}{32}$	.00390	167.5
2 Poldi	650	166500	"	.00390	167.5
3 Styrian	668	171100	"	.00390	122.2
4 Novo	441	113100	"	.00390	132.0
5 A. & W.	523	134200	"	.00390	124.8
6 McInnes	434	111200	"	.00390	90.3
7 Poldi	498	127700	"	.00390	95.9
8 A. & W.	454	116300	"	.00390	109.8
9 Styrian	422	108100	"	.00390	102.4
10 Novo	482	123500	"	.00390	111.2
11 Poldi	1179	147100	$\frac{1}{8} \times \frac{1}{16}$	.00802	167.5
12 A. & W.	978	122000	"	.00802	122.2
13 A. & W.	695	86700	"	.00802	132.0
14 McInnes	1134	141500	"	.00802	124.8
15 Styrian	704	87800	"	.00802	90.3
16 Poldi	855	106500	"	.00802	109.8
17 Novo	717	89500	"	.00802	102.4
18 McInnes	692	86300	"	.00802	111.2
19 A. & W.	706	88100	"	.00802	95.9
20 Novo	1410	117500	$\frac{3}{16} \times \frac{1}{16}$	.01200	122.2
21 Styrian	1264	105300	"	.01200	124.8
22 Poldi	1219	101500	"	.01200	132.0
23 Novo	989	82400	"	.01200	90.3
24 McInnes	958	79800	"	.01200	95.9
25 Styrian	1123	93700	"	.01200	109.8
26 A. & W.	967	80600	"	.01200	111.2
27 Poldi	1012	84500	"	.01200	102.4
28 Rex	1271	106000	"	.01200	123.2

V. Summary of Results

(*a*) *Variation of Cutting Force with Area of Cut*

The effort exerted by the tool in cutting was determined as explained in Part III (c). The horse-power lost in driving the lathe and countershaft was deducted from the total horse-power used during the trial, the difference being the net horse-power required for cutting. This was reduced to foot-pounds per minute, and divided by the cutting speed, giving the force exerted. The figures so obtained were reduced to pounds per unit area of cut, and plotted as ordinates upon a base of area of cut in Fig. 14. The curves show that the cutting force was not directly proportional to the area of cut, but decreased as the area increased, and that the average cutting force varied from 50 tons per square inch for soft cast iron to 85 tons per square inch for hard cast iron. Each curve shown in the figure represents a different hardness of cast iron. The relative hardness is shown in the table on the figure.

(*b*) *Variation of Durability of Tool with Cutting Speed*

In Fig. 15 are shown the curves which represent the relation between the durability of the tool and the cutting speed. These are important curves. Each curve represents a different hardness of cast iron. Referring to the middle curve, which is for cast iron of medium hardness, it will be seen that a cutting speed of 50 feet per minute is satisfactory, the durability being 100. If the speed is increased very materially, the durability decreases quite rapidly. It is evident that for each hardness of cast iron, the cutting speed allowable for a maximum durability exists where the vertical line indicating cutting speed is tangent to curves similar to those drawn.

(*c*) *Variation of Cutting Speed with the Hardness of Cast Iron*

The curve shown in Fig. 16 represents the advisable cutting speed on cast iron of varying hardness. This curve represents the result of all the tests of the different steels tested. This curve shows: (a) that any of the steels tested can remove very hard cast iron at a rate of 25 feet per minute; (b) that all of the steels tested begin to wear rapidly at speeds a little above 125 feet per minute. Between these two points the relation between a safe cutting speed and the hardness of the cast iron seems to be defi-

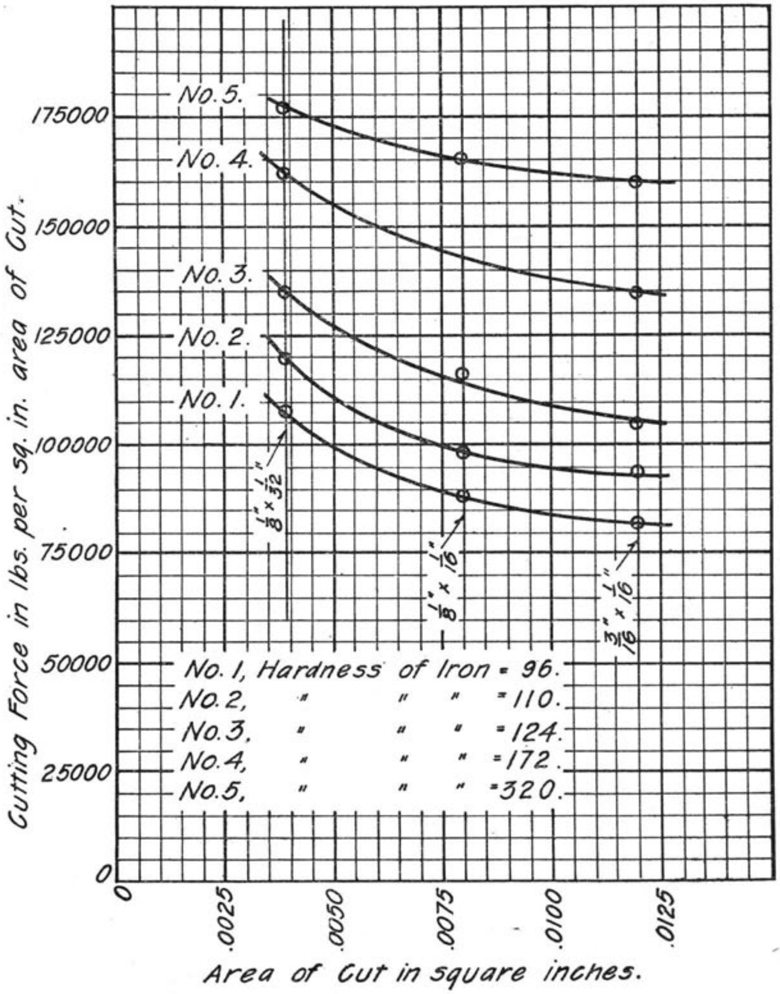

Fig. 14. Curves Showing Relation Between Cutting Force on Point of Tool and Area of Cut for Cast Iron of Varying Hardness

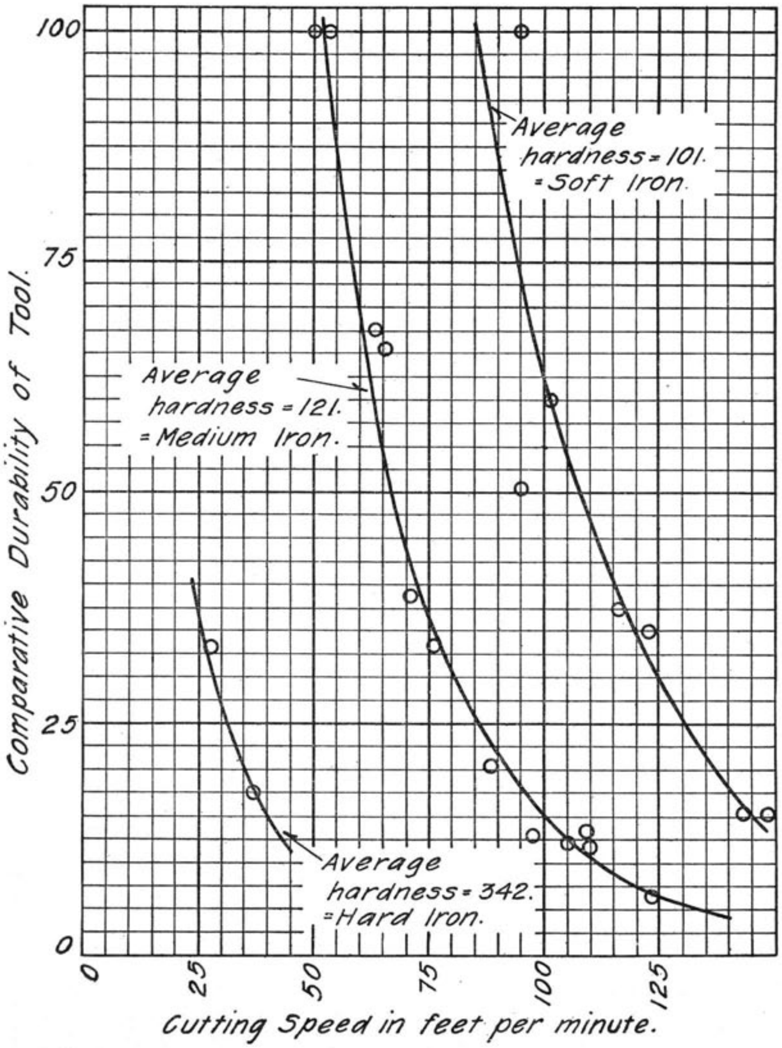

FIG. 15. CURVES SHOWING VARIATION OF DURABILITY OF TOOL WITH CUTTING SPEED FOR CAST IRON OF VARYING HARDNESS—AVERAGE OF ALL TOOL STEELS

nitely expressed by the curve. It would seem that cast iron of medium hardness, 100 to 120, could be cut at 125 feet per minute just as readily as at 70 feet per minute, as far as any injury to the tool is concerned. It must be remembered that this curve does not take into account the effect, on the cutting speed, of the variation in the area of cut; the experiments from which the

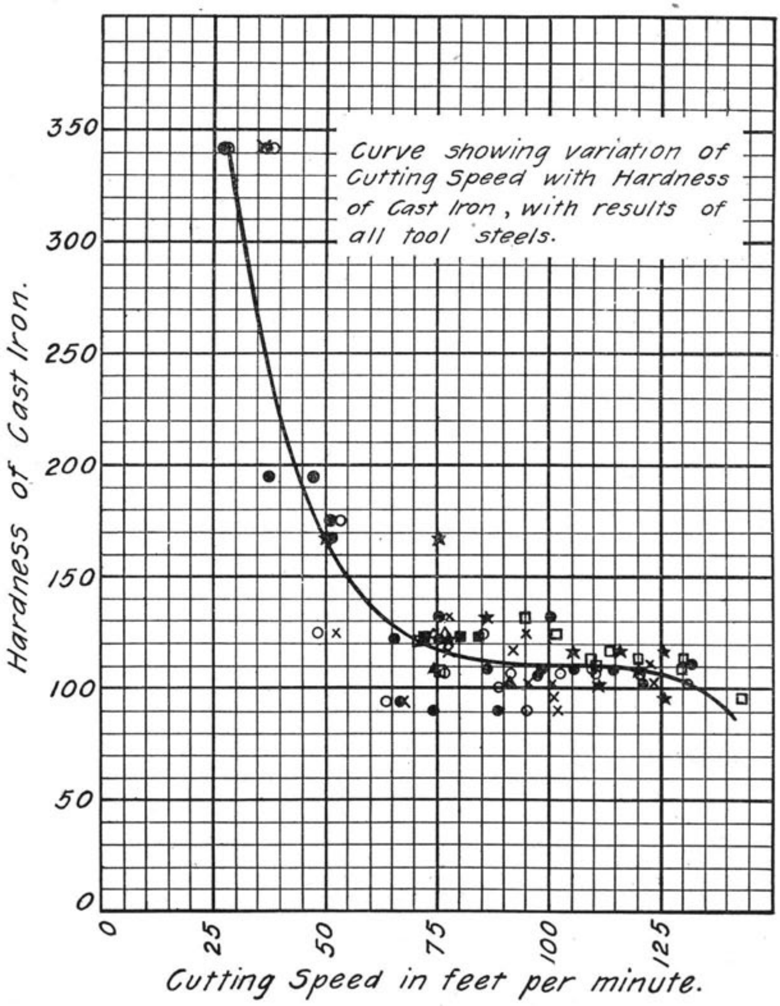

FIG. 16. CURVE SHOWING CUTTING SPEEDS IT IS ADVISABLE TO USE WITH A VARIATION IN THE HARDNESS OF CAST IRON

curve was plotted were in all cases those in which the cut was very nearly $\frac{1}{8}$ in. depth of cut by $\frac{1}{16}$ in. feed, so that there is but a slight variation in the area of cut in all of the experiments. From the curve of Fig. 16, we find the cutting speeds given in Table 4 to be applicable to the grades of iron manufactured by the different companies sending test pieces. In order that any company may make use of the curve shown in this figure, it will be necessary simply to determine the average hardness of its cast iron, as explained elsewhere, and where the horizontal line representing this hardness cuts the curve, the possible safe cutting speed may be read on the scale below. This curve should prove useful to various manufacturers.

TABLE 4

ALLOWABLE CUTTING SPEEDS FOR GRADES OF CAST IRON USED IN THE TESTS

Name of Company Sending Test Pieces		Average Hardness of Test Pieces	Allowable Cutting Speed
American Radiator Co....., Chicago, Ill.	Pierce Plant	101.8	132.0
	Michigan Plant..........	110.7	118.0
	Detroit Plant............	109.3	120.0
	——— Plant.......... Marked 5-17-05	112.7	90.0
	——— Plant.......... Marked B 5-26-05	138.1	60.0
	——— Plant.......... Marked B 6-2-05	103.1	132.0
Crane Company..........., Chicago, Ill.	Grey Iron	132.0	63.0
	Ferro-Steel.............	342.0	28.0
Root, Van Dervoort Eng'g Co. ...., East Moline, Ill.		175.2	48.0
University of Illinois.. ...., M. E. Dept. Shops.		136.3	60.0

(*d*) Generally speaking, all the steels tested proved equally effective. It is very evident that there are great possibilities ahead for high-speed steels. Before realizing their full benefit, however, certain advances must be made. Heavier machine tools must be built. The capacity of the motors and power plants must be increased. Special hardening furnaces with temperature measuring devices must be available. More must be known concerning the chemical and physical properties of the various steels. (*e*) Tool steels are now available that will cut cast iron from two to three times as fast as was possible a few years ago. When every advantage has been taken of these possibilities, the cost of manufacturing many articles should be materially reduced.

VI. Reference List of Articles on High-Speed Steels

Experiments with a New Tool Steel: by F. Heissig, in *Stahl and Eisen*, January 1, 1901.

Results of tests made by Böhler Bros. and Co., Vienna and Berlin, on their Styrian Steel marked Böhler Rapid.

Extract of Report of Experiments of Taylor and White, at the Bethlehem Steel Co., S. Bethlehem, Pa.: in *Zeitschrift des Vereines Deutscher Ingenieure*, March 30, 1901.

The Taylor-White Process of Treating Tool Steel and Its Influence on the Mechanic Arts: by Charles Day, in *Journal of the Franklin Institute*, September, 1901.

High-Speed Steel: in *Zeitschrift des Vereines Deutscher Ingenieure*, September 28, 1901.

Report of experiments instituted by the Berlin section of the Vereines Deutscher Ingenieure. Test made on forged and cast steel and cast iron.

High-Speed Tool Steel: by F. Reiser, in *Stahl and Eisen*, January 15, 1903.

A discussion of the chemical properties of high-speed and self-hardening tool steels.

Speeds, Feeds and Angles of Metal-Cutting Tools: by F. Donaldson, in *American Machinist*, March 5, 1903.

Discussion of the relation of cutting angles to angles to which tools are ground.

The Requirements of Machine Tool Operation with Special Reference to the Motor Drive: by Charles Day, in *American Machinist*, Part 1, March 12, 1903, Part II, March 19, 1903.

Discussion of tools driven by electricity.

Metal Cutting with the New Tool Steels: by Oberlin Smith, in *Engineering Magazine*, April, 1903, Vol. 25.

Discussion of changes in the design and operation of machines to be wrought by the new tool steels.

Notes on High-Speed Tool Steels: by Henry H. Suplee, in *Engineering*, (London), July 31, 1903, Vol. 76.

Results of tests made at the Union Pacific Shops, Omaha, Nebraska.

Rapid Tool Steels: in *Engineering* (London), August 21, 1903, Vol. 76.

Chemical properties of the new steels with attainable speeds. Editorial.

Rapid-Cutting Tool Steels: in *Engineering* (London) October 30, 1903, Vol. 76.

Report on experiments made at the Manchester Municipal School of Technology under the direction of a joint committee from the above school and the Manchester Association of Engineers. A very elaborate and interesting report by Professor J. T. Nicolson, also reported in the American Machinist, November 19 and 26, 1903.

The Analysis of High-Speed Steels: in *Engineering* (London), November 20, 1903, Vol. 76.

Methods of testing for different chemical constituents

Cutting Speeds and Feeds with New Tool Steels: by Oberlin Smith, in *Engineering Magazine*, January, 1904, Vol. 26.

Record of actual results obtained.

Rapid-Cutting Steel: by Professor J. T. Nicolson, in *Technics*, January, 1904.

A very interesting summary of Berlin and Manchester experiments. The following formula is deduced:

$$V = \frac{K}{a + L} + M$$

V = allowable cutting speed in feet per minute

a = area of cut in square inches

K, L, M = constants for different materials

See Table 5. The chemical analyses to which these tables apply are given in Table 6. It is probable that these results were obtained under the most favorable conditions

and therefore represent the maximum results obtainable at the time of these experiments. It is a question whether these results can be attained in the work shop, where the conditions are frequently not so favorable.

TABLE 5

CONSTANTS FOR USE IN THE EQUATION GIVING THE RELATION BETWEEN CUTTING SPEED AND AREA OF CUT

(Experiments by Nicolson)

Constant	Fluid Pressed Steel			Cast-Iron Bars		
	Soft	Medium	Hard	Soft	Medium	Hard
K	1.950	1.850	1.030	3.100	1.650	1.300
L	.011	.016	0.160	.025	.030	.035
M	15.000	6.000	4.000	8.000	7.000	5.500

TABLE 6

CHEMICAL COMPOSITION OF MATERIALS REFERRED TO IN TABLE 5

(Experiments by Nicolson)

	Fluid Pressed Steel			Cast-Iron		
	Soft	Medium	Hard	Soft	Medium	Hard
Carbon	.198	.275	.514	.....	....	.....
Combined Carbon	.....	....	.....	.459	.585	1.1500
Graphite	.....	....	.....	2.603	2.720	1.8750
Silicon	.055	.086	.111	3.010	1.703	1.7890
Manganese	.605	.650	.792	1.180	.588	.3480
Sulphur	.026	.037	.033	.031	.061	.1614
Phosphorus	.035	.043	.037	.773	.526	.7320

The Heat Treatment of Steel: in *Proceedings of the Institute of Mechanical Engineers*, January, 1904, Sixth Report of the Alloys Research Committee.

Discussion of hardening, annealing and chemical properties of steel.

The Introduction of High-Speed Steels in Engineering Work Shops: in *Engineering* (London), March 4, 1904, Vol. 77.

High-Speed Tool Steel: Its Manufacture and Use: by J. M. Gledhill, in *Technics*, Part I, June, 1904; Part II, July, 1904.
Some constituents and processes used in the manufacture of high-speed steel.

Experiments with a Lathe-Tool Dynamometer: by Professor J. T. Nicolson, in *Trans. A. S. M. E.*, Vol. 25, 1904.
Measures all forces acting on a lathe tool while cutting. Valuable for designers of lathes. Discussion of influence of cutting angles on power required to cut.

A Twist Drill Dynamometer: by Wm. W. Bird and Howard O. Fairfield, in *Trans. A. S. M. E.*, Vol. 26, 1904.
Measures both the twist and torque of drill while cutting with high-speed drills.

The Chemical Analysis of High-Speed Steels and Alloys: by Fred Ibbotson, in *Technics*, October, 1904.

The Development and Use of High-Speed Tool Steel: by J. M. Gledhill, in *American Machinist*, December 22, 1904.
Interesting results of experiments made to find the effect of various chemical constituents on the cutting powers of the tool steel.

Feeds and Speeds for Lathe Work: by T. A. Sperry, in *American Machinist*, May 25, 1905.
Results of observations at the shops of the Cincinnati Milling Machine Company.

High-Speed Steel in the Factory: by O. M. Becker and Walter Brown, in *Engineering Magazine*, beginning September, 1905.
Conclusions of a practical study of the use of high-speed steel and its introduction into the factory.

Economy of High-Speed Steel Tools: by F. D. Smith and H. S. Greene. Thesis for a degree in Electrical Engineering in the College of Engineering, University of Illinois, June, 1905.
Tests made at the Chicago and Eastern Illinois Railway Shops, Danville, Illinois, showing that the cost of removing a pound of metal with low-speed steel is from 2.2 to 4.8 times as great as when using high-speed steel.

APPENDIX

Instructions for Hardening the Steels Used furnished by the makers.

(1) Directions for working Styrian Steel, marked Böhler Rapid

For Forging:

Heat to a bright red. Do not allow the heat to run as low as a cherry-red while forging. After forging allow the tool to cool slowly before hardening.

For Hardening: Lathe, Planer and Boring Tools.

Heat to a white heat but not to a scaling or melting point, just a good white heat. Cool in the air or a cold blast.

HOUGHTON AND RICHARDS,
American Agents.

(2) Directions for working Jessop's "Ark" High-Speed Steel

For Forging:

Heat the steel to a canary color, retaining this heat until the tool is forged as nearly as possible to the shape required. The tool may be rough finished by grinding while yet hot on a dry emery wheel. It should then be laid aside in a dry place until black.

For Hardening:

Place the nose of the tool in a clear fire. Slowly heat the steel to a white or welding heat, not over one inch from the end. The nose of the tool should be made fusing hot. Then it should be placed under a strong, cold, dry air blast until cold.

WILLIAM JESSOP AND SONS, Limited,
New York.

(3) Directions for working McInnes's "Extra" High-Speed Air-Hard Steel

For Forging and Hardening:

Forge the steel at the ordinary tool-steel forging heat; after the tool is forged to the desired shape, reheat the cutting end to a light cherry-red, and cool in an air blast. In order to bring out the quality of this steel when the tool is forged to the above instructions, it should be run at high speed in the lathe or planer until the edge is worn off two or three times and reground. After each grinding the tool gets better until it gets to its limit.

McInnes's Steel Company, Limited,
Corry, Pennsylvania.

(4) Directions for working Mushet "Special" High-Speed Steel

For Hardening:

When forged, the cutting end of the tool should be reheated to a white heat, and then immediately blown cold. While hot this steel must be kept from water.

(5) Directions for working "Air Novo" High-Speed Tool Steel

For Forging:

The steel must be heated thoroughly, so that it is hot all the way through. The forging color must be a very light yellow. Do not hammer the steel when it gets down to a dark red, but reheat it. After the tools are forged lay them down to cool.

For Hardening:

Heat the cutting edge only of the tool to a white welding heat. Heat it until it begins to flow. Then put the tool into a compressed air blast, or dip immediately into thin lard, linseed or fish oil until thoroughly cold.

Hermann Boker & Co.,
New York.

(6) Directions for working "Rex" High-Speed Tool Steel

For Forging:

Use a clean fire and forge at a bright red heat, holding the steel at this heat as nearly as possible while the forging is being done. Forging at too low a heat will cause the steel to burst in forging. When tool is forged lay it down in a dry place to cool.

For Hardening:

Use a clean fire or furnace and bring the point or cutting portion of the tool gradually to a sweating white heat. This heat is indicated by a flux, having the appearance of melted borax, forming on the nose of the tool. Confine the high heat as much as possible to the cutting portion of the tool. When the proper heat is reached, take from the fire and carefully remove the oxide scale which instantly forms on the heated portion of the tool. This can be done with a coarse file, and will permit the cutting portion of the tool to cool off much more uniformly and rapidly than if the oxide scale is allowed to remain. When extremely hard and tough metal is to be machined, blow cold in fan or dry compressed air blast.

CRUCIBLE STEEL COMPANY OF AMERICA,
Pittsburg, Pa.

The directions received from the American Radiator Company for hardening the two foreign steels, "A & W" and "Poldi", applied to nipple dies. The same, however, were used in the tests for lathe tools, with the exception of being heated in a forge fire. They are as follows:

(7) For Hardening "A & W" High-Speed Tool Steels, manufactured by Armstrong, Whitworth and Company, Limited, England:

"When tempering the steel for nipple dies, we placed the dies in a retort, and heated them so that the cutting end reached a white heat; then the dies were placed in a strong air blast and cooled to a cherry-red color, after which they were dropped into a tempering oil. Tempering in this manner gives by far the best wearing point to the steel".

(8) Directions for Hardening "Poldi" High-Speed Tool Steel:

"This steel was treated in a slightly different manner from the 'A & W'. The dies were heated to a white heat in a retort, and then cooled in an air blast until they were absolutely cold."